Review of the non-structural considerations for seismically retrofitting hospitals, impact on hospital functionality, and hospital selection

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SECTION 1

Introduction and background

For many years the design and assessment of structural components and systems[1] was the focus of most seismic codes worldwide. Although this focus remains dominant, experience in recent earthquakes has shown that damage to nonstructural components is also of great concern. A nonstructural component is any architectural element; mechanical, electrical, plumbing (MEP) equipment or systems or part thereof; or any furniture, fixtures, equipment (FF&E) or building contents. This term is used to describe any and all components of a building structure which are not an explicit part of the structural system. For example, in the US, provisions in ASCE/SEI 7-10 (Chapter 13) govern the seismic design of nonstructural components. Previous studies by FEMA (FEMA, 2007; 2011 amongst others) have shown that nonstructural components constitute a major investment in most buildings; therefore, the failures of these elements may be both dangerous and costly. In fact, the failure of nonstructural components during seismic events may result in injuries or fatalities; cause costly damage to buildings and their contents; and force the closure of residential, medical and manufacturing facilities, businesses, and government offices until appropriate repairs are completed. To quantify the potential consequences of earthquake damage to nonstructural components, three types of risk can be typically considered:

- Life Safety (LS): Could anyone be hurt by this component in an earthquake?
- Property Loss (PL): Could a large property loss result?
- Functional Loss (FL): Could the loss of this component cause an outage or interruption?

For more detailed descriptions of the above definitions, one may refer to FEMA E-74 (FEMA, 2011).

These preliminary remarks also apply to hospitals and medical facilities. In a typical hospital, the nonstructural components play a major role in health operations and account for a large share of initial and replacement/repair costs. Typically, for a medium-size hospital, the structure accounts for around 15% of the total cost, and the nonstructural components account for the remaining 85% (FEMA, 2007). Of the latter, the mechanical, electrical, and plumbing systems alone account for approximately 35% of the total building cost (FEMA, 2007). Even though the building structure may be relatively undamaged after an earthquake, excessive structural motion may cause damage to ceilings, partitions, light fixtures, service piping, and exterior walls and glazing. In addition, storage units, medical equipment, and filing cabinets may topple and cause injuries if not properly anchored or braced. Excessive motion may also lead to damage to rooftop equipment, and localised damage to water systems and fire suppression piping and sprinklers. Heavy equipment, such as machinery, kilns, and heavy mechanical and electrical equipment, may also be displaced and become non-functional.

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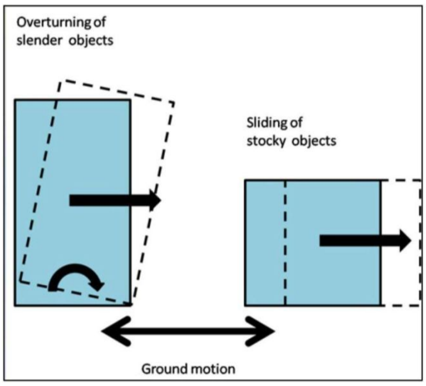
[1] A structural system is the combination of all structural components, such as beams, columns, floors, structural walls etc. that are explicitly designed to carry loads such as gravity, earthquake, wind, etc. The nonstructural components of a building include all building parts and contents except for those previously described as structural.

Under catastrophic events such as earthquakes, it is important to ensure the unhindered operation of key buildings, such as hospitals. Continued hospital operation is mainly dependent on nonstructural components and systems, including medical and building equipment. Hospital operations also depend on specialised services, some of which involve storing of hazardous substances, such as pharmaceuticals, toxic chemicals, oxygen and other gases, all of which must be prevented from spilling/leaking. Distribution systems for hazardous gases must be well supported and braced. Furthermore, hospitals require a very extensive plumbing network to supply water throughout the building, and an adequate piping network to supply water for fire sprinklers, which increases the risk of secondary water damage in cases of failure of these systems during earthquakes.

There are many factors affecting the performance of nonstructural components during an earthquake and the extent to which they will sustain damage. Specifically, there are four principal causes of damage to nonstructural components (FEMA, 2011), namely:

- **Inertial forces**
  When a building shakes during an earthquake, the base of the building typically moves with the ground. The entire building and its contents above the base experience inertial forces that push them back and forth in a direction opposite to the base excitation. When unrestrained or marginally restrained items are shaken during an earthquake, inertial forces may cause them to slide, rock, or overturn (e.g. Figure 1). For example, file cabinets, emergency generators, suspended items, free-standing bookshelves, office equipment, and items stored on shelves or racks can all be damaged as they move and interact with other items, fall, overturn or become disconnected from attached components. The shaking can also cause damage to internal components of equipment without any visible damage or movement from its original location.

Figure 1 Sliding and overturning due to inertial forces. Image from: FEMA E-74 (FEMA, 2011).



- **Building deformations.**
  During an earthquake, structural components of buildings can deform, bend or stretch and compress in response to earthquake forces. When the building deforms, the columns or walls deform and any windows or partitions rigidly attached to the structure must also deform or displace by the same amount. Brittle materials such as glass, plaster partitions, and masonry infill or veneer cannot tolerate any significant deformation and will crack. Once cracked, the inertial forces in the out-of-plane direction can cause portions of these architectural components to become dislodged and to fall far from their original location, possibly injuring passers-by underneath them.

- **Separation or pounding effects between separate structures**
  Another source of nonstructural damage involves pounding or movement across separation or expansion joints between adjacent structures or structurally independent portions of a building. A seismic joint is the separation or gap between two different building structures, often two wings of the same facility, which allows the structures to move independently from one another. In order to provide functional continuity between adjacent structures or between structurally independent portions of a building, utilities must often extend across these building joints. Flashing, piping, conduit, fire sprinkler lines, heating, ventilation, and air-conditioning (HVAC) ducts, partitions, and flooring all have to be detailed to accommodate the seismic movement expected at these locations when the two structures move closer together or further apart. Damage to items crossing seismic separation or expansion joints is a common type of earthquake damage. If the size of the gap is insufficient, pounding between adjacent structures may result, which can damage structural components but more often causes damage to nonstructural components, such as parapets, veneer, or cornices on the façades of older buildings.

- **Interaction between adjacent nonstructural components**
  An additional source of nonstructural damage is the interaction between adjacent nonstructural systems which move in different ways from one another. Many nonstructural components may share the same space in a ceiling plenum or pipe chase; these items may have different shapes, sizes, and dynamic characteristics, as well as different bracing requirements. Some examples of damaging nonstructural interactions include:

  1) Sprinkler distribution lines interact with the ceiling causing the sprinkler heads to break and leak water into the room below.
  2) Adjacent pipes of differing shapes or sizes are unbraced and collide with one another or adjacent objects.
  3) Suspended mechanical equipment swings and impacts a window, louver, or partition.
  4) Ceiling components or equipment can fall, slide, or overturn blocking emergency exits.

The level of damage associated with the above mentioned causes depends on various considerations, such as the components' dynamic characteristics, their location in the building, and their proximity to other structural or nonstructural components. Other factors include the:

- Type of ground motion
- Structural system of the building
- Location and placement of the loads
- Type of anchorage or bracing, if any
- Strength of the structural supports used for anchorage
- Potential interaction with other nonstructural components
- The potential for secondary damage

SECTION 2

Key nonstructural components

2.1 Nonstructural components for non-specialist buildings

As discussed, the nonstructural components of a building include all building parts and contents generally specified by architects, mechanical engineers, electrical engineers, and interior designers. However, they may also be purchased and installed directly by owners or tenants after construction of a building has been completed. For example, in commercial real estate, the architectural and mechanical, electrical, and plumbing systems may be considered a permanent part of the building and belong to the building owner; the furniture, fixtures, equipment and contents, by contrast, typically belong to the building occupants.

More specifically, the non-structural components are mainly divided into three categories:

- Architectural components: such as partitions, ceilings, storefronts, glazing, cladding, veneers, chimney, fences, and architectural ornamentation.
- Mechanical, electrical, and plumbing components: such as pumps, chillers, fans, air handling units, motor control centres, distribution panels, transformers, and distribution systems including piping, ductwork and conduit.
- Furniture, fixtures and equipment: such as shelving and book cases, industrial storage racks, retail merchandise, books, medical records, computers and desktop equipment, wall and ceiling mounted TVs and monitors, file cabinets, kitchen, machine shop or other specialty equipment, industrial chemicals or hazardous materials, museum artifacts, and collectibles.

The list of nonstructural components is extensive and constantly evolving as new technologies alter the built environment.

During an earthquake, the resulting ground motions shakes a structure and the structure shakes everything that is in it or on it, including the building envelope[2] and components of the interior nonstructural systems. For example, damage to architectural systems consists of broken windows and cracked exterior walls and interior partitions. In extreme cases, exterior walls and partitions can topple completely. Ceilings are also vulnerable to damage and can break into small pieces or fall to the floor (for example see Figure 2). Damage to the building service systems can consist of sliding or overturning of equipment like boilers, generators, and fans, or swaying and possible fracture of mechanical ducts, pipes, and electrical conduit.

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[2] A building envelope is the physical separator between the conditioned and unconditioned environment of a building including the resistance to air, water, heat, light, and noise transfer.

Figure 2 Example of nonstructural damage during an earthquake. Image adapted from FEMA 577 (FEMA, 2007).

2.2 Key nonstructural components for hospitals

Although earthquakes damage structural components in similar ways, nonstructural damage depends on the building’s use. For instance, buildings with special occupancies and functions, such as hospitals, require much more detailed and accurate damage descriptions than those needed for other ordinary buildings. The effects of earthquake damage on hospital operations and the safety of occupants are described in the literature mostly based on the experiences of hospitals in the United States. Historically, buildings have been engineered to provide adequate life safety to occupants and passers-by from earthquake hazards, particularly in areas of high seismic risk. For most buildings, life safety is primarily threatened by building collapse or the debris falling into the street and neighbouring buildings. A higher level of performance is required to address the life safety issues of hospitals, since patients often have limited mobility and are dependent on caregivers or specialised medical equipment.

Figure 3 Example of nonstructural (highlighted) elements found in hospital facilities. Image adjusted from FEMA 577 (FEMA, 2007).

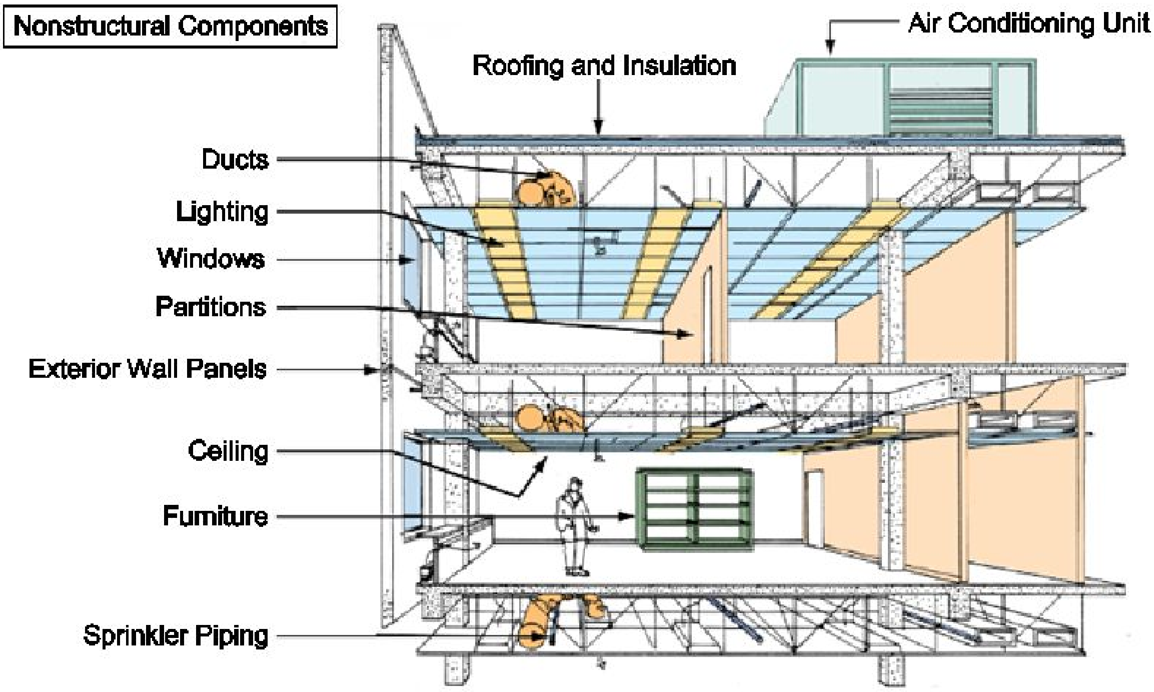


Figure 3 shows typical nonstructural components present in most hospital facilities. The building envelope includes the systems that separate the interior spaces from the exterior, both structural and nonstructural. It includes exterior walls and cladding, roof systems, doors and windows, and floors or slabs that separate the building interior from the ground. Contents and equipment are completely dependent on the type of occupancy and the function of the space, and range from items such as furniture encountered in a lobby or a waiting room, to highly technical equipment commonly present in treatment rooms. In addition, laboratories, pharmacies, bulk storage areas, and large central energy plants have highly specialised and frequently very sensitive equipment. In general, both the building service systems and the contents of hospitals rank among the most complex and expensive of any building type. Furthermore, both the structural system and most of the nonstructural systems are required to perform without interruption after an earthquake to enable adequate functionality.

In general, since the contents and equipment within hospitals varies substantially, damage types also vary widely. For example, medical equipment, such as operating tables and lights, radiation and X-ray units, sterilizers, and patient monitors, is often heavy and not well anchored to the structure. Offices and storage rooms, such as the areas used to store critical supplies, medicine, medical records, chemicals, and fuel, can also be severely damaged by shaking.

With regard to equipment, Guragain et al (2004) created a list of typical hospital equipment, which is tabulated below (Table 1).

The seismic codes worldwide usually categorise nonstructural components as architectural components or mechanical and electrical components. Many of the hospital contents, such as furnishings and specialised equipment, which may be critical to hospital function, are not subject to building codes.

S.N.	Name of Equipment	S.N.	Name of Equipment
1	Anesthesia machine with ventilator	38	Laparoscopy equipment
2	Autoclave	39	Lontofor equipment
3	Automatic cell counter	40	Microcentrifuge
4	Bilirubin meter	41	Microscopes
5	Biochemical analyzer	42	Miscellaneous equipment
6	Blood bank freezer	43	MRI machine
7	Boilers	44	Operating table
8	Centrifuge	45	Osmometers
9	Circuit Boards	46	Ovens
10	Clinical files	47	Oxygen concentrator
11	CT scanner	48	Oxygen Cryogenic tank
12	Culture incubator	49	Oxygen cylinders
13	Dialysis unit	50	Oxygen Tanks
14	Dryers	51	Pavilion lamp
15	Electrical photometer	52	Piping
16	Electrocardiogram defibrillator monitor	53	Plate developers
17	Electrodiathermy	54	Plate processing equipment
18	Electrostimulator	55	Power generator
19	Elevator controls	56	Pulmonary function analyzer
20	Elevator engine	57	Pulse oxymeter
21	Elevator pulleys	58	Respirators
22	ELISA analyzer	59	Shelves
23	Emergency power generator	60	Steam system
24	Ethylene oxide sterilizer	61	Sterile and non-sterile material storage
25	Flame photometer	62	Suction machine and pumps
26	Gamma chambers	63	Telephone switchboard
27	Gas analyzer	64	Transformer
28	Gas Connection	65	Ultrasound
29	Gas cookers	66	Urine analyzer
30	Geiger counter	67	Vital signs monitors
31	Hemodialysis machines	68	Washing machines
32	Image intensifier	69	Waste disposal
33	Incubator	70	Water pump system
34	Industrial freezer	71	Water tanks
35	Infusion pump	72	X-ray equipment
36	Kitchen equipment		
37	Lamp		

Table 1 List of typical hospital equipment. (Guragain et al., 2004)

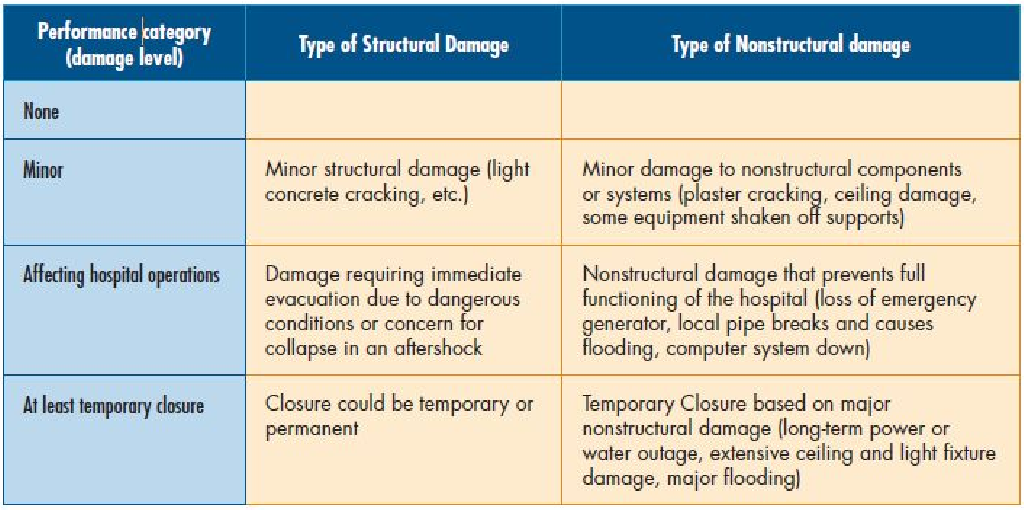
SECTION 3

Seismic vulnerability of nonstructural components in hospitals

As discussed in D'Ayala et al. (2015a), seismic vulnerability of a hospital facility is a measure of the damage the building is likely to experience when subjected to ground shaking of a specified intensity. The response of a structure to ground shaking is complex and depends on a number of interrelated parameters that are often very difficult, if not impossible, to predict precisely. These include:

- The exact character of the ground shaking the building will experience.
- The extent to which the structure will respond to the ground shaking.
- The strength of the materials in the building.
- The quality of construction, the condition of individual structural elements and of the whole structure.
- The interaction between structural and nonstructural elements.
- The live load in the building at the time of the earthquake.

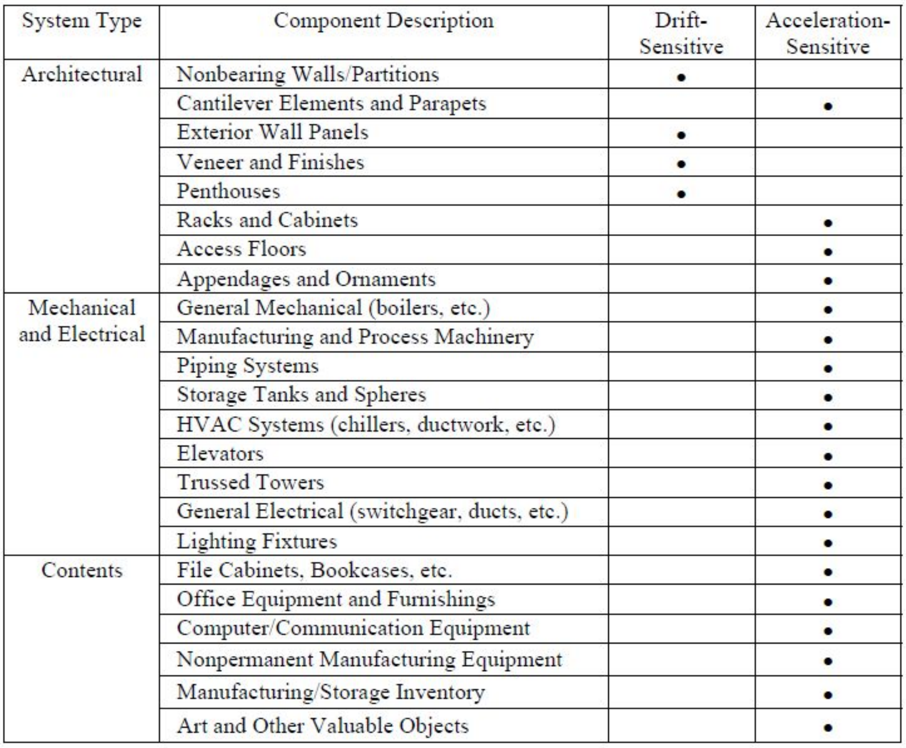
A simple preliminary vulnerability assessment of existing hospitals can be performed using the results of the historical study of hospital performance in a variety of seismic events. For example, a recently completed study on ‘Seismic Vulnerability of Hospitals Based on Historical Performance in California’ (Holmes and Burkett, 2006) analysed the historical record of losses to hospitals damaged in major California earthquakes since 1971. Damage reports varied from brief, one-paragraph summaries to elaborate narratives of the damage patterns and the consequences. Evacuations or ‘shut-downs’ of facilities were always noted. These descriptions were used to categorise hospital damage into one of the structural and nonstructural performance categories shown in Table 2.



Performance category (damage level)	Type of Structural Damage	Type of Nonstructural damage
None		
Minor	Minor structural damage (light concrete cracking, etc.)	Minor damage to nonstructural components or systems (plaster cracking, ceiling damage, some equipment shaken off supports)
Affecting hospital operations	Damage requiring immediate evacuation due to dangerous conditions or concern for collapse in an aftershock	Nonstructural damage that prevents full functioning of the hospital (loss of emergency generator, local pipe breaks and causes flooding, computer system down)
At least temporary closure	Closure could be temporary or permanent	Temporary Closure based on major nonstructural damage (long-term power or water outage, extensive ceiling and light fixture damage, major flooding)

Table 2 The description of performance categories in terms of structural and nonstructural building damage. (FEMA, 2007)

These categories, based on past damage experienced, provide a clearer picture of the vulnerability of hospitals and established a benchmark for vulnerability assessments of all the existing hospitals.



System Type	Component Description	Drift-Sensitive	Acceleration-Sensitive
Architectural	Nonbearing Walls/Partitions	•	
	Cantilever Elements and Parapets		•
	Exterior Wall Panels	•	
	Veneer and Finishes	•	
	Penthouses	•	
	Racks and Cabinets		•
	Access Floors		•
	Appendages and Ornaments		•
Mechanical and Electrical	General Mechanical (boilers, etc.)		•
	Manufacturing and Process Machinery		•
	Piping Systems		•
	Storage Tanks and Spheres		•
	HVAC Systems (chillers, ductwork, etc.)		•
	Elevators		•
	Trussed Towers		•
	General Electrical (switchgear, ducts, etc.)		•
	Lighting Fixtures		•
Contents	File Cabinets, Bookcases, etc.		•
	Office Equipment and Furnishings		•
	Computer/Communication Equipment		•
	Nonpermanent Manufacturing Equipment		•
	Manufacturing/Storage Inventory		•
	Art and Other Valuable Objects		•

Table 3 *HAZUS* Classification of Drift-Sensitive and Acceleration-Sensitive Nonstructural Components and Building Contents

In the HAZUS program (FEMA, 2010; https://www.fema.gov/hazus), to better estimate different types of loss, building damage functions (loss vs shaking intensity) separately predict damage to:

- The structural system.
- Drift-sensitive (i.e. due to building deformations; see Section 1) nonstructural components, such as partition walls that are primarily affected by building displacement.
- Acceleration-sensitive (i.e., due to inertial forces; see Section 1) nonstructural components, such as suspended ceilings, that are primarily affected by building shaking.

Building contents are also considered to be acceleration sensitive. Distinguishing between drift and acceleration-sensitive nonstructural components, and contents, permits more realistic estimates of likely damage. Table 3 lists typical drift-sensitive and acceleration-sensitive components and building components.

SECTION 4

Retrofitting strategies for nonstructural factors

Design of structural and nonstructural risk reduction measures is similar for new and existing hospitals. New hospital design offers the possibility to minimise the risk by selecting a site likely to be subjected to less ground motion, with better soil conditions, or located further from a fault. It can be designed with the most appropriate structural system, using known and tested materials and a good building configuration. These possibilities are not available when retrofitting an existing hospital. The existing building may have been designed to an obsolete seismic code or no code at all, its materials may be questionable, or the building configuration and structural system may be inappropriate. Therefore, protecting an existing hospital must start with a detailed evaluation of its vulnerability (D'Ayala et al., 2015a and 2015b), because seismic retrofitting is both disruptive and expensive, and should not be implemented without careful study.

It is relatively easy to incorporate, for example, seismic bracing and anchoring during ongoing renovation or rehabilitation work. However, a more active and reliable retrofitting programme requires development of databases of components and systems, and developing a process for prioritising the interventions. Priorities can be set by considering importance to life safety, importance to overall functionality, associated cost and disruption, component vulnerability, or by cost-benefit considerations (for example see Section 5).

Components commonly found to be of high priority because of their importance, high level of vulnerability, and relatively low cost include anchorage of standby generators, medical gas storage, pressurised piping, and communications systems. It is important that the key vulnerabilities of each facility are identified and considered in emergency planning and mitigation programmes.

4.1 Summary of Risk Reduction Measures for Existing buildings

Achieving cost-effective improvements in seismic performance of existing facilities is far more complex than improving expected performance for proposed new buildings in the planning and design stage. It is always far less expensive to include relatively small changes in a new design to create seismically resistant structural and nonstructural systems than it is to retrofit—or sometimes replace—existing systems. The complexity and expense of retrofitting is exacerbated when such work is not done in conjunction with complete renovation—that is, if the building has to remain mostly occupied and operational. Following the recommended seismic evaluations, careful analysis is needed to identify significant life safety risks from potential structural collapse; to identify and achieve short-term, high cost-benefit mitigation measures; and to plan for longer-term overall mitigation.

The following steps are recommended:

- Engage a structural engineer (or a team of structural engineers) experienced in seismic evaluation and design to perform a seismic structural evaluation of existing buildings on the campus that contribute to the hospital function. The primary purpose of such an analysis is to quickly identify buildings that may be seriously damaged or even collapse under earthquakes of expected intensity, as defined in the local seismic code. A secondary purpose is to gain an understanding of the probable performance of the structural and nonstructural systems of each building.

- Engage a specialist team consisting of an architect, mechanical, electrical and structural engineers, in order to evaluate the probable seismic performance of nonstructural components and systems.
- Update the emergency response plan, considering the results of the seismic evaluations, with particular focus on nonstructural elements. An emergency plan that considers the care of the patients and staff of the facility, as well as the surrounding community, should be kept up to date and should include a realistic estimation of the seismic performance of the structural and nonstructural systems in each building, and on the site in general.
- If significant life safety risks are identified from review of either structural or nonstructural systems, make plans to minimise occupancy of the building, replace the building, or retrofit to an acceptable level of performance.
- Vulnerable medical buildings that can lose full functionality after a code earthquake should be studied for retrofit or replacement. Improvements in seismic structural performance can often be combined with major renovations. Adjacent additions can sometimes be made sufficiently strong to reinforce an existing building.

The most vulnerable elements that can affect the functions of the hospital have been identified from past earthquakes, and are the following:

- Emergency generator
- Bulk oxygen storage tank
- Internal and external emergency communication systems
- Patient elevators

Apart from elevators, these elements normally can be anchored and braced against seismic damage inexpensively and quickly. The elevators may require extensive retrofit to assure operation after strong shaking. However, to assure safe patient relocation immediately after an event, it is recommended that one patient elevator serving each floor be retrofitted. Automatic seismic switches that demobilise elevators at low shaking levels should be used with caution, as the switch may defeat the purpose of the strengthened elevator. Mechanical equipment on vibration isolators that are not designed for seismic forces are extremely vulnerable to seismic damage. This equipment should be identified and fitted with appropriate seismic isolators, or seismic snubbers, as soon as possible.

Incremental seismic rehabilitation (ISR), as described in FEMA 396 (FEMA, 2003), should also be considered for applicability. ISR consists of a series of discrete rehabilitation actions that result in an effective, affordable, and non-disruptive strategy for responsible mitigation action. ISR is divided into three main parts:

- Part A, Critical Decisions for Earthquake Safety in Hospitals
- Part B, Planning and Managing the Process for Earthquake Risk Reduction in Existing Hospital Buildings
- Part C, Tools for Implementing Incremental Seismic Rehabilitation in Existing Hospital Facilities

The Hospital Seismic Safety Evaluation Checklist (APPENDIX A) should be applied.

4.2 Nonstructural mitigation

Nonstructural mitigation involves retrofitting a building's non-structural elements. A breakdown of common non-structural mitigation techniques is presented below.

1. **Brace Exterior Elements** – Reduce or eliminate damage to exterior elements (parapets, chimneys, exterior facing, windows, and doors) by bracing, strengthening, reinforcing, or replacing elements or connections to withstand earthquake forces. Mitigation measures include:

- Bracing parapets
- Anchoring or replacing cornices and architectural elements
- Bracing chimneys
- Securing wall panel anchors
- Bracing large windows
- Replacing window glass

2. **Anchor Interior Elements** – Anchor interior non-structural elements (non-load bearing interior walls, partition walls, suspended ceilings, and raised computer floors) by strengthening or reinforcing elements or connections to withstand earthquake forces and movements. Mitigation measures include securing of un-braced suspended (drop) ceilings and overhead lighting fixtures with wires and struts, bracing of interior partitions, and anchoring raised computer floors at their pedestal supports.

3. **Protect Building Electrical, Mechanical, and Plumbing Systems** – Anchor heavy building utility equipment and secure utility connections and supply lines to protect them against earthquake forces and movements. Heavy building utility equipment can be anchored by protecting springs on vibration isolators, securing gas tanks with metal straps, and bracing and restraining elevator counterweights and rails. Utility connections and supply lines can be secured by bracing overhead utility pipes and HVAC ducts with metal brackets, installing flexible pipes or conduits at connections, and installing seismic shutoff valves on gas lines.

4. **Secure Building Contents** – Secure furnishings and other building contents to reduce movement from earthquake-induced ground shaking. Desktop computers and equipment can be restrained with chains, cables, clips, or cords. Metal anchors can be used to secure bookcases and large filing systems to floors, walls, or each other. Hazardous materials and other miscellaneous furnishings (tables, chairs, cubicle wall partitions, wall hangings, etc.) can be secured with straps, anchors, angle brackets, and sturdy hooks. Other mitigation techniques that may be included under non-structural mitigation include earthquake hazard mitigation planning and preparedness.

More specifically, twelve applicable mitigation measures, which have been effective in many cases, are described below.

i. Removal is probably the best mitigation option in many cases. An example is a hazardous material that could be spilled, but it could be stored perfectly well outside the premises. Another example would be the use of a very heavy covering in stone or concrete on the outside of the building, which could easily come loose during an earthquake. One solution would be better fastenings or the use of stronger supports, but the most effective solution would be removal and replacement.

ii. Relocation would reduce danger in many cases. For example, a very heavy object on top of a shelf could fall and seriously injure someone, as well as breaking and causing economic losses. If it is relocated to a floor-level shelf it would not represent any danger to human lives or to property.

iii. Restricted mobility for certain objects such as gas cylinders and power generators is a good measure. It does not matter if the cylinders shift as long as they do not fall and break their valves. Sometimes back-up power generators are mounted on springs to reduce the noise and vibrations when they are working, but these springs would amplify ground motion. Therefore, restraining supports or chains should be placed around the springs to keep the generator from shifting or being knocked off its stand.

iv. Anchorage is the most widely used precaution. It is a good idea to use bolts, cables or other materials to prevent valuable or large components from falling or sliding. The heavier the object, the more likely it is that it will move due to the forces produced by an earthquake. A good example is a water heater, of which there will probably be several in a hospital. They are heavy and can easily fall and break a water main. The simple solution is to use metal straps to fasten the lower and upper parts of the heater against a firm wall or another support.

v. Flexible couplings sometimes are used between buildings and outside tanks, between separate parts of the same building, and between buildings. They are used because the separate objects each move independently in response to an earthquake: some move quickly, others slowly. If there is a tank outside the building with a rigid connection pipe that joins them together, the tank will vibrate at frequencies, directions and amplitudes that are different to those of the building, causing the pipe to break. A flexible pipe between the two would prevent ruptures of this kind.

vi. Supports are suitable in many cases. For example, ceilings are usually hung from cables that only withstand the force of gravity. When subjecting them to the horizontal stresses and torsion of an earthquake, they easily fall. They can cause serious injury to people who are underneath them and obstruct evacuation routes.

vii. Substitution by something that does not represent a seismic hazard is appropriate in some situations. For example, a heavy tiled roof does not only make the roof of a building heavy, it is also more susceptible to the movement of an earthquake. The individual tiles tend to come off, creating a hazard for people and for objects. One solution would be to change it for a lighter, safer roofing material.

viii. Modification is a possible solution for an object that represents a seismic hazard. For example, earth movements twist and distort a building, possibly causing rigid glass in the windows to shatter and launch sharp glass splinters onto the occupants and the passers-by around the hospital. Rolls of transparent adhesive plastic may be used to cover the inside surfaces and prevent them from shattering and threatening those inside. The plastic is invisible and reduces the likelihood of a glass window causing injuries.

ix. Isolation is useful for small, loose objects. For example, if side panels are placed on open shelves or doors with latches on the cabinets, their contents will be isolated and probably will not be thrown around if an earthquake were to occur.

x. Reinforcement is feasible in many cases. For example, an unreinforced infill wall or a chimney may be strengthened, without great expense, by covering the surface with wire mesh and cementing it.

xi. Redundancy or duplication of items is advisable. Emergency response plans that call for additional supplies are a good idea. It is possible to store extra amounts of certain products, providing a certain level of independence from external supplies which could be interrupted in the case of earthquakes.

xii. Rapid response and repair is a mitigation measure used on large oil pipelines. Sometimes it is not possible to do something to prevent the rupture of a pipeline in a given place, therefore spare parts are stored nearby and arrangements are made to enter the area quickly in case a pipe breaks during an earthquake. A hospital should have spare plumbing, power and other components on hand, together with the suitable tools, so that if something is damaged repairs can be easily made. For example, during an earthquake the water pipes may break; it may be impossible to take prior measures to totally eliminate this risk, but it should be possible to ensure that everything necessary for quick repair is at hand. With prior earthquake planning it is possible to save the high costs of water damage with a minimum investment in a few articles.

SECTION 5

Prioritisation strategies for retrofitting

5.1 Benefit-Cost Analysis (BCA)

The FEMA Benefit-Cost Analysis (BCA; FEMA, 2004) software provides a standardised, systematic process for evaluating the benefits of a mitigation project and for comparing these benefits to the project costs. A complete BCA counts all of the significant direct benefits of a mitigation project and involves revaluating damage and losses before mitigation and after mitigation. For mitigation projects that affect life safety, a BCA must also consider the statistical monetary value of casualties avoided. The benefits of a mitigation project are the difference in expected damage and losses before and after the mitigation project is completed. A BCA also accounts for the probabilities of various levels of natural hazards, damage, the useful life of the mitigation project, and the time value of money, or discount rate.

In particular, when performing a BCA, the following factors must be evaluated (FEMA, 2004):

- **Probability** - a measure of how likely it is that some event will occur
- **Vulnerability** - susceptibility to damage
- **Value** - an amount considered a fair and suitable equivalent for something

The benefits considered are avoided damage and losses that are expected to accrue as a result of the mitigation project. The costs considered are those necessary to implement the specific mitigation project under evaluation. Costs are generally determined for projects with engineering design studies. Benefits, however, must be estimated based on probability because they depend on the improved performance of the building or facility in events, the timing and severity of which also must be estimated on probability.

The benefits considered include:

- Avoided damage to the building and contents
- Avoided displacement costs
- Avoided rental and business income losses
- Avoided loss of public/non-profit services
- Avoided casualties.

The benefits calculated by the programme are expected benefits that are estimated over the useful lifetime of the mitigation project. To account for the time value of money, a net present value calculation must be performed. This calculation is done automatically in the programme, using the discount rate and project useful life entered by the analyst. Results of a BCA are presented in two ways: first, the benefit-cost ratio (BCR), which is benefits divided by costs, and second, the present value criterion (benefits minus costs).

For BCAs, several inputs are required to determine the total value of lost public or nonprofit services (also known as functional downtime) from earthquake damage to the building. Note that these values apply only to public and nonprofit service buildings, and default estimates of functional downtime will vary based on building damage at various levels of earthquake intensity.

The cost assessment is based on two primary considerations: project cost and maintenance cost. The project cost is the total, upfront cost of designing and installing a given mitigation measure as part of a retrofit to an existing building, excluding maintenance costs. Some non-structural earthquake mitigation projects such as securing furniture are simple measures with no design costs and minimal labour and material costs; while others are more complex and require engineering analysis and higher labour and material costs. The lower the mitigation project cost, the more likely that the project will be cost-effective. The project cost for mitigation measures should be based on current year costs and may be obtained from the applicant’s proposal, estimated based on design and construction costs provided by a contractor, or using a nationally recognised unit cost guide.

The maintenance cost is the long-term costs of maintaining the effectiveness of a given mitigation measure. Maintenance costs are an important consideration in determining the true value of a non-structural earthquake mitigation project for several reasons. Some low-cost mitigation measures can have high maintenance costs that increase the overall project cost and lower cost-effectiveness. Also, mitigation measures with high maintenance costs are often less effective over time which can reduce the BCR. Finally, maintenance costs may be an indication that the mitigation project employs active measures that are generally less effective than passive measures.

5.2 Multi-Criteria Decision Making (MCDM)

A Multi-Criteria Decision Making (MCDM) method, known as TOPSIS (Technique for Order Preference by Similarity to Ideal Solution: Hwang and Yoon, 1981), can be used for the selection of the optimal retrofit strategy (structural or nonstructural) in the case of an existing (under-designed) hospital.

The decision process is made of the following eight steps:

(1) Assessment of the un-retrofitted structure.
(2) Definition of the set of alternatives.
(3) Design of the retrofit options.
(4) Selection of the evaluation criteria.
(5) Relative weighting of the criteria.
(6) Evaluation of the alternatives.
(7) Application of the chosen MCDM method to rank the alternatives and to identify the best retrofit solution.
(8) Sensitivity analysis to investigate the stability of the solution in respect to the weights of the criteria (Caterino et al, 2008, 2009).

Some of the procedure’s steps require choices which are, to a certain extent, subjective; this includes the relative weighting of the criteria and the qualitative evaluations of the alternatives. In these cases, the role of who has to choose the retrofit solution, the decision maker (DM), is important.

The criteria are generally conflicting with each other or representing trade-offs. In most cases, there is no solution that satisfies all criteria simultaneously. In fact, criteria can be generally distinguished as ‘benefit’ type, when the DM is interested in maximising the evaluation of alternatives according to them, and “cost” type, when the DM wants to minimise them.

Before applying any MCDM methods, all the alternatives have to be evaluated according to each criterion. This requires the qualitative variables to be converted into numbers and the criteria weights to be determined.

The evaluation of the alternatives according to the different criteria generally involves variables characterised by different units of measure. In these cases, a normalisation of the involved variables may be needed. Qualitative criteria are often also involved in the decision process. This kind of criteria, by definition, requires evaluation through linguistic judgment. As a consequence, the conversion of these qualitative evaluations in equivalent numbers is needed to completely define the decision matrix.

A detailed review of the different MCDM solution methods is presented in Caterino et al (2009). In particular, the weighted sum model (WSM) is the best known and simplest MCDM method for evaluating a number of alternatives in terms of a number of decision criteria. It is very important to state here that it is applicable only when all the data are expressed in exactly the same unit. If this is not the case, then the final result is equivalent to “adding apples and oranges.″

In general, suppose that a given MCDA problem is defined on *m* alternatives and *n* decision criteria. Furthermore, let us assume that all the criteria are benefit criteria, that is, the higher the values are, the better it is. Next suppose that w_j denotes the relative weight of importance of the criterion C_j and a_{ij} is the performance value of alternative A_i when it is evaluated in terms of criterion C_j. Then, the total (i.e. when all the criteria are considered simultaneously) importance of alternative A_i, denoted as $A_i^{\text{WSM-score}}$, is defined as follows:

$$A_i^{\text{WSM-score}} = \sum_{j=1}^{n} w_j a_{ij}, \text{ for } i = 1, 2, 3, \ldots, m.$$

For the maximisation case, the best alternative is the one that yields the maximum total performance value.

It is worth noting that both methodologies presented here have not been used in comparable contexts, (i.e. for application to hospital and medical facilities, although they represent state-of-the-art procedures (e.g. Caterino et al, 2008, 2009).

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Glossary

ANCHORAGE: Connection or attachment of a nonstructural component to the structure typically through the use of welding, bolts, screws, post-installed anchors or other mechanical fasteners that provide a positive connection. Based on the configuration and the deformability of the components used, the anchorage may behave as a rigid attachment or a flexible attachment.

BASE: The portion of a building embedded in or resting on the ground surface. Seismic forces are delivered to the base of a building. This term is also used to describe the interface of a freestanding nonstructural component with the floor or roof of a building where it is supported. Seismic forces from the floor or roof level of the building are delivered to the base of the nonstructural component.

DAMAGE: Physical evidence of inelastic deformation of a structural component caused by a damaging earthquake.

DRIFT: The horizontal displacement of a building resulting from the application of lateral forces, usually forces from an earthquake or wind. See also interstorey drift.

FOUNDATION: That part of a structure which serves to transmit vertical and lateral forces from the superstructure of a building to the ground.

FRAME: A type of structural system in which the loads are carried by a grid or framework of beams and columns, rather than by load-bearing walls. Special purpose frames built up from struts or steel shapes are used to support many types of nonstructural components such as piping, ducts, etc.

GLAZING: Glass or a transparent or translucent plastic sheet used in windows, doors, and skylights.

GROUND MOTION: The movement of the earth’s surface from earthquakes or explosions. Ground motion is produced by waves that are generated by a sudden slip on a fault or sudden pressure at the explosive source, and travel through the earth and along its surface.

INERTIAL FORCES: Forces necessary to overcome the tendency for a body at rest to stay at rest or for a body in motion to stay in motion.

INTENSITY: See Shaking Intensity.

INTERSTOREY DRIFT: The horizontal displacement that occurs over the height of one story of a building resulting from the application of lateral forces, usually forces from an earthquake or wind. This is often expressed as an interstorey ratio; the ratio of the displacement to the height of the story. Interstorey drifts from the structural design of a building are often needed in design calculations for nonstructural components such as glazing, pipe risers or precast panels that are attached to more than one floor.

LIFE SAFETY: A performance level whereby a building may experience extensive damage to structural and nonstructural components, but remains stable and has significant reserve capacity.

MITIGATION: An action taken to reduce the consequences of a future earthquake. Other terms such as retrofit, rehabilitation or upgrade are also used to describe these actions.

NONSTRUCTURAL COMPONENT: Any architectural element; mechanical, electrical, plumbing (MEP) equipment or systems or part thereof; any furniture, fixtures, equipment (FF&E) or building contents. This term is used to describe any and all components of a building or nonbuilding structure which are not an explicit part of the structural system.

PARTITION: A nonstructural interior wall used to subdivide interior spaces. Partitions may span horizontally or vertically from support to support; support may be provided by the building structure or secondary framing members. Partitions may be full-height or partial-height, often stopping just above the ceiling level and are typically constructed of steel or wood studs and gypsum board, wood studs and plaster, brick, or concrete masonry unit infill. Glass block and glazed partitions are also in use.

POUNDING: The impact of two structures during an earthquake. Pounding frequently occurs when the seismic gap between two adjacent wings of a building, or the gap between two neighbouring buildings, is insufficient to accommodate the relative lateral movement of both buildings.

REPAIR: An action taken to address a damaged building component.

RESTRAINT/BRACING: Bracing or anchorage used to limit movement under seismic forces. Cables or rigid elements (struts, pipes, angles, etc.) used to resist forces by uniaxial tension or compression. The term “bracing” may also be used to describe design to resist lateral forces through the use of wall or frame elements.

RIGID CONNECTION: The anchorage of an object to a structural member or braced nonstructural component, usually using hardware such as bolts or brackets, which is designed to prohibit the object to move relative to the structural member or braced nonstructural component.

SEISMIC FORCE: The force that will act on a nonstructural component during an earthquake is the product of its mass and the seismic acceleration.

SEISMIC RISK: The chance of injury, damage, or loss resulting from earthquake activity.

SHAKING INTENSITY: The amount of energy released by an earthquake as measured or experienced at a particular location. Intensity is subjectively measured by the effects of the earthquake on people and structures.

SHEAR WALL: A wall designed to resist lateral forces parallel to the wall.

STRUCTURAL COMPONENT: A structural member such as a beam, column, or wall that is an individual part of a structural element

SUPPORTS: Those members, assemblies of members or manufactured elements including braces, frames, legs, shear lugs, snubbers, hangers, saddles, struts, and associated fasteners that transmit loads between nonstructural components and their attachments to the structure. Some supports may carry only gravity loads (the weight of the item), such as vertical hangers. Some supports may resist both gravity loads and seismic loads; some may resist only seismic loads.

TORSION: Twisting around an axis. The centre of the mass does not coincide with the centre of resultant force of the resisting building elements causing rotation or twisting action in plans and stress concentrations. Symmetry in general reduces torsion.

Appendix A Checklist for seismic vulnerability of hospitals during design and construction

The checklist for Seismic Vulnerability of Hospitals (Table below) is a tool that can be used to help assess site-specific seismic hazards and building vulnerability. The checklist is useful during site selection, preliminary design of a new building, or when considering rehabilitation of an existing facility. In addition to examining building design issues that affect vulnerability, the checklist also helps users to examine the functionality of the critical and emergency systems upon which most hospitals depend. The checklist is organised into separate sections, so that each section can be assigned to a subject expert for greater accuracy of the examination. The results should be integrated into a master vulnerability assessment to guide the design process and the choice of appropriate mitigation measures.

Vulnerability Sections	Guidance
Site Condition	
Is there an active fault on or adjacent to the site?	If suspected, site-specific geologic investigations should be performed. Consult local building department, State geologist, local university, or local geotechnical expert.
Does the site consist of soft, stiff, or dense soil or rock?	If the presence of softer soil that can lead to force amplification or liquefaction is suspected, site-specific geologic investigations should be performed.
Are post-earthquake site egress and access secured?	Alternative routes — unlikely to be blocked by falling buildings, power lines, etc.— are desirable.
Are utility and communications lifelines vulnerable to disruption and failure?	Security of the entire utility and communications network is the issue: the facility may be affected by offsite failures.
Are there alternate or backup sources for vital utilities such as water and power?	System redundancy increases the probability of the hospital remaining functional after an event.

Vulnerability Sections	Guidance
Architectural	
Is the architectural/structural configuration irregular?	Irregular vertical and horizontal configurations, such as setbacks, open first stories, or L- or T-shaped plans, may lead to significant stress concentrations.
Is the building cladding attached to structural frames so that it can accommodate drift?	Frames are flexible, and cladding must be detailed to accommodate calculated drifts and deformations. If waterproofing of these systems is compromised, rain following an earthquake could cause parts of the building to be closed.
Are heavy veneers, such as brick or stone, securely attached to the structural walls?	Shear wall structures are very stiff and carry large earthquake forces; heavy attachments must be securely attached.
Are glazing and other panels attached so that they can accommodate drift?	Glazing must be installed with sufficient bite and adequate space between glass and metal to accommodate drift.

Vulnerability Sections	Guidance
Are light, suspended grid ceilings and lights braced and correctly attached at walls?	Suspended ceilings, if not braced, easily distort (particularly in light and flexible frame structures), thus causing ceiling panels to fall out.
Are heavy plaster suspended ceilings securely supported and braced?	Heavy lath and plaster ceilings in older facilities are very dangerous if poorly supported.
Are partitions that terminate at a hung ceiling braced to the structure above?	Partitions need support for out-of-plane forces, attachment to a suspended ceiling grid only is inadequate.
Are masonry or hollow tile partitions reinforced, particularly those surrounding exit stairs?	Heavy partitions attract strong earthquake forces because of their stiffness and mass, and are prone to damage. They are particularly dangerous around stairs and exit ways.
Are parapets and other appendages securely braced and attached to the building structure?	Unreinforced masonry parapets are especially vulnerable. Brace items such as cornices, signs, and large antennas.

Vulnerability Sections	Guidance
Structural System	
When was the existing structure designed?	Buildings with no, or outdated, seismic design are unlikely to perform adequately in strong shaking. Verify that the Importance Factor was used in design.
Has the local seismic zoning changed significantly since the building was designed?	Local expectation of shaking intensity can change as scientific knowledge increases
Is there a continuous load path from all components of the building to the foundation?	A continuous load path assures that the structure will act together as a whole when shaken. Connections from walls to floors and roofs should also form part of this load path.
Is all load-bearing structural masonry reinforced according to code?	Older unreinforced masonry has proven very vulnerable in strong shaking.
Are horizontal diaphragms correctly designed and constructed with necessary chords and collectors?	Large diaphragm openings and the edges of diaphragms need careful design to ensure forces are properly transmitted to walls and frames.

Vulnerability Sections	Guidance
Nonstructural System	
Are there backups for critical municipal utilities?	Municipal utilities such as water, power, and gas, are often disrupted in strong shaking. Onsite backups should provide 48 hours of use.
Are ducts, piping, conduit, fire alarm wiring, and communication systems that pass through seismic joints provided with flexible connections?	Differential movement between sections of the building can cause breakage and leaks in pipes and ducts if no provision is made for movement. If walls at joint are firewalls, penetrations should be fireproofed.

Vulnerability Sections	Guidance
Is heavy mechanical equipment adequately secured?	Heavy equipment may slide and break utility connections.
Are vibration isolators for vibrating equipment designed for seismic forces?	Equipment may jump off very loose isolators and may break restraints designed for wind only.
Is the piping properly braced and provided with expansion joints?	
Is ductwork properly supported and braced?	
Are boilers and other tanks securely braced?	Gas heaters or tanks with flammable or hazardous materials must be secured against toppling or sliding.
Are plumbing lines adequately supported and braced?	Leaks in pressure pipes can cause damage over a large area. Protection of joints is especially important.
Is fire protection piping correctly installed and braced?	
Is heavy electrical equipment adequately secured?	Switch gear and transformers are heavy and sliding or movement failure can shut down the electrical system.
Is emergency generator and associated equipment secured against movement?	The generator, muffler, batteries, day tank, and other electrical equipment may be necessary for emergency operation.
Are suspended lighting fixtures securely attached, braced, or designed to sway safely?	Older suspended lighting fixtures have performed badly in earthquakes, and are an injury hazard.
Are light fixtures supported in an integrated ceiling, braced, and provided with safety wires?	Light fixtures within a grid often fall when the grid is distorted, unless the fixtures are secured with safety wires.
Are the elevator cars, counterweights, and equipment anchored for seismic forces?	Elevators are important for patient movement, particularly in an emergency. After strong shaking, elevators and shafts should be checked for safety before use.
Is at least one elevator in each wing connected to the emergency power system?	Even if properly anchored and undamaged, the elevator needs power to enable vertical patient movement.
Is the bulk oxygen tank and associated equipment secured?	The legs, anchorage, and foundations of large tanks need to be checked for adequacy.
Is nitrogen storage secured?	Loose tanks may fall and break connections.
Are small natural gas lines to laboratories or small equipment vulnerable?	Incompatibility of large and small lines and equipment movement can cause dangerous leaks.
Is the fire alarm system connected to a secondary power supply?	This is also necessary to support daily operational needs, including lighting, heating, communications, etc.

Vulnerability Sections	Guidance
Is significant fire alarm equipment secured against movement?	Equipment can slide or topple, breaking connections. See FEMA 74.