NONSTRUCTURAL DESIGN PHILOSOPHY 9

by Gary McGavin

9.1 INTRODUCTION

This chapter builds on the knowledge previously presented and discusses the issue of seismic design for nonstructural components and systems. Initially, the primary purpose of seismic design was the desire to protect life safety. Buildings were designed so that the occupants could safely exit the facility following a damaging earthquake. Damage to buildings has always been allowed by the code, even to the extent that the building might need to be demolished following the event, even if correctly designed according to the seismic code. Until very recent years, with minor exceptions, nonstructural design has been minimally required by the model building codes.

The lack of attention to nonstructural systems and their increasing complexity have resulted in the majority of dollar losses to buildings in recent earthquakes. These losses are the result both of the direct cost of damage repair and of functional disruption while repairs are undertaken. Today, good seismic design requires that both structural and nonstructural design be considered together from the outset of the design process. Figures 9-1 and 9-2 illustrate such a design.

Landers Elementary School was constructed and occupied just prior to the magnitude 7.3 Landers earthquake in 1992. The building was situated just 0.4 mile from approximately 10 feet of horizontal offset along the fault trace and experienced severe shaking. Nonstructural damage was minor and included cracked stucco and dislodged suspended ceiling

Figure 9-1: Successful integration of structural and nonstructural design. Landers Elementary School, designed by Ruhnau-McGavin-Ruhnau Associates, 1990.

Figure 9-2: Limited nonstructural damage at Landers Elementary.

tiles in the multipurpose room. In the magnitude 6.5 Big Bear earthquake, which occurred three hours after the Landers event, at the school a water line broke and a hot water heater restraining strap failed due to the incorrect use of lag bolts (too short and not anchored into the studs). The hot water heater remained upright and functional.

As more building owners recognize the necessity to remain operational following a major event, architects will be called upon to provide designs that go beyond the minimal code requirements for life safety and exiting. As our existing stock of older buildings is seismically retrofitted, the nonstructural components and systems must also be seismically retrofitted to the same level as the structure.

9.2 WHAT IS MEANT BY THE TERM "NONSTRUCTURAL"

Nonstructural systems and components within a facility are all those parts of a building that do not lie in the primary load-bearing path of the building and are not part of the seismic resisting system. In general, they are designed to support their own weight, which is then transferred to the primary structural system of the building. The number and complexity of nonstructural systems and components far outnumber the structural components of a building. Figure 9-3 shows the basic structural and nonstructural systems.

While nonstructural components are not intended to contribute to seismic resistance, nature does not always respect this distinction. Rigid

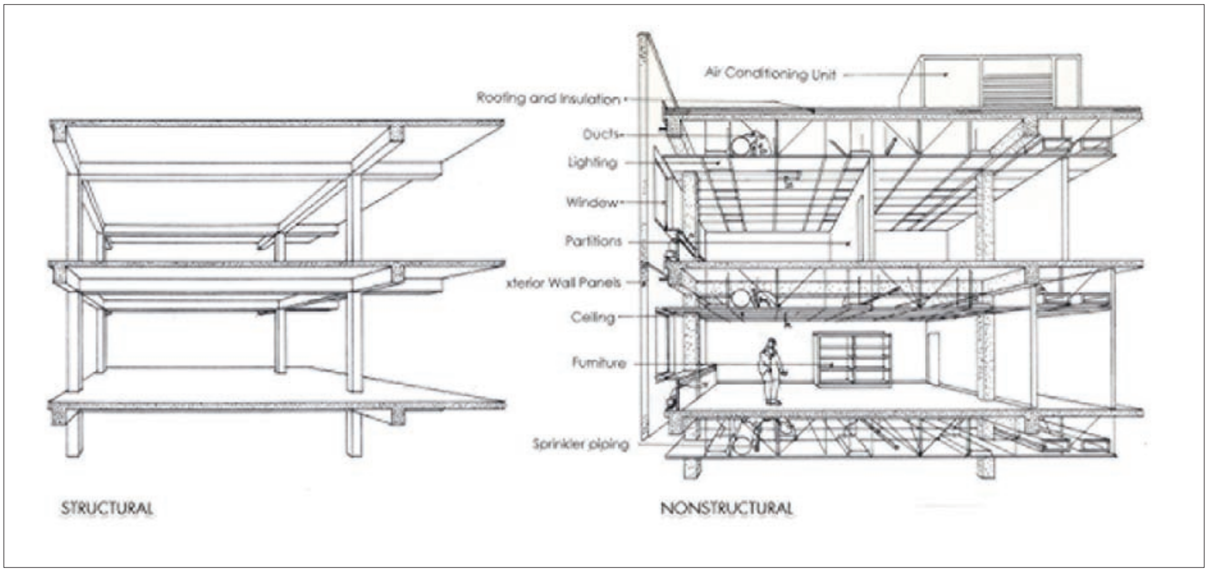


Figure 9-3: The basic structural system (left) and the nonstructural components (right).

nonstructural walls spanning between structural columns will change the local stiffness of the structural system and alter its rsponse, possibly creating a stress concentration. Partitions may suddenly be called upon to perform a supporting role, as seen in Figure 9-4. Conversely, structural members may act in a nonstructural manner if, for example, the contractor omits placing the steel reinforcing in a reinforced concrete wall.

The number and complexity of nonstructural systems and components is very large. A typical broad categorization includes the following:

Figure 9-4: Nonstructural partition walls prevented the total collapse of this unreinforced masonry structure in the 1983 Coalinga earthquake.

- Architectural
- Electrical
- Mechanical
- Plumbing
- Communications
- Contents and Furniture

A more specific list of nonstructural components based on the *International Building Code* (IBC) are categorized as architectural, mechanical, and electrical and is shown below. The IBC also provides design coefficients for each category that are applied to the component to establish the design seismic force.

9.2.1 Architectural Components

Interior nonstructural walls and partitions
Cantilever elements
  Parapets
  Chimneys
Exterior nonstructural wall elements and connections
  Light wall elements (metal insulated panels)
  Heavy wall elements (precast concrete)
    Body of panel connections
    Fasteners of the connecting systems
Veneer
  Limited deformability elements
  Low deformability elements
Penthouse (separate from main building structure)
Ceilings
  Suspended
  Attached to rigid sub-frame
Cabinets
  Storage cabinets and laboratory equipment
Access floors
Appendages and ornamentation
Signs and billboards
Other rigid components
Other flexible components

9.2.2 Mechanical and Electrical Components

General mechanical
- Boilers and furnaces
- Pressure vessels freestanding and on skirts
- Stacks
- Large cantilevered chimneys

Manufacturing and process machinery
- General
- Conveyors (nonpersonnel)

Piping system
- High deformability elements and attachments
- Limited deformability elements and attachments
- Low deformability elements and attachments

HVAC system equipment
- Vibration isolated
- Nonvibration isolated
- Mounted in-line with ductwork

Elevator components

Escalator components

Trussed towers (freestanding or guyed)

General electrical
- Distributed systems (bus ducts, conduit, cable trays)
- Equipment

Lighting fixtures
- Surface mounted to structure
- Suspended from structure
- Supported by suspended ceiling grid, surface mounted, or hung from suspended ceiling

9.2.3 Consequences of Inadequate Nonstructural Design

Historically, the seismic performance of nonstructural systems and components has received little attention from designers. The 1971 San Fernando earthquake alerted designers to the issue' mainly because well-designed building structures were able to survive damaging earthquakes while nonstructural components suffered severe damage. It became obvious that much more attention had to be paid to the design of nonstructural components. Some investigators have postulated that nonstructural system or component failure may lead to more injury and death in the future than structural failure.

The following are the basic concerns for nonstructural system/component failure:

- Direct threat tolife
- Indirect threat to life
- Loss of building function (loss of revenue and service)
- High repair costs

9.3 NONSTRUCTURAL SEISMIC DESIGN AND "NORMAL" SEISMIC DESIGN

Designing for earthquakes has historically been the domain of the structural engineer. This publication has shown elsewhere what forces are brought to bear on buildings, how the building can be expected to respond due to the earthquake event, what effects the local soils have on the building, and how the building will transmit seismic forces from the foundation up through the structure of the building. By definition, the nonstructural systems and components of the building are attached to the building's primary structure or, in the case of furniture and unsecured equipment/contents, rest unattached on the floors of the building. Seismic forces are generally amplified as they travel up from the foundation through the building to the top of the structure. These increased forces are transmitted to the nonstructural components at their interface with the structure. Many nonstructural systems and components are often very flexible, in contrast to the relatively rigid building structure. This flexibility often leads to a much higher level of excitation than the building's primary structure.

9.4 EFFECTS OF IMPROPER NONSTRUCTURAL DESIGN

There are a number of objects that can directly cause either death or injury if they are not properly designed for restraint (Figures 9-5 and 9-6). These injuries are generally due to falling hazards, such as large sections of plaster ceilings, HVAC registers, lights, filing cabinets, etc. There are also indirect threats to life and injury due to nonstructural failures. These might include the inability of occupants to safely exit a building due to damaged materials strewn across the stairs in exit stairwells (Figure 9-6).

Although is this example was not a result of an earthquake, the MGM Grand Hotel Las Vegas fire in the 1980s serves to illustrate the complexity of nonstructural design. The fire activated the emergency power supply. The building construction included re-entrant corners that required a large seismic joint between building units. This joint in effect provided a chimney within the building that was not air tight between the floors. The continued operation of the emergency power supply unit caused the asphyxiation of several occupants, since the HVAC system had its fresh air intake close to the exhaust of the emergency power. Thus, occupants died due to smoke inhalation and carbon monoxide poisoning in part due to the seismic design of the nonstructural systems.

Figure 9-5: Falling objects can be a direct threat to life, as can be envisioned in this example, had children been sitting in the seats in this elementary school library in Coalinga in 1983.

In some cases, nonstructural failure can cause a loss of function of the building. While this may not be critical for some building occupancies, it is very undesirable in others such as hospitals, emergency operations centers, police stations and communications centers. Unfortunately, failures are often caused by system or component interactions. In addition, more and more owners of commercial and industrial facilities are recognizing the need for continued operation in order to reduce financial loss following a damaging earthquake. Hospitals have a need for both continued function and reduction of economic loss. The owner-supplied equipment and contents within a hospital are often significantly more valuable than the building itself. Medications and bandages that are soaked due to flooding from broken fire sprinkler lines cannot be used when they are most needed. The sophisticated equipment within a hospital will take more time to repair, and be more costly, if damaged, than the equipment in an office building or a school.

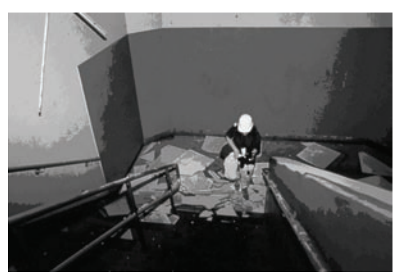


Figure 9-6: Difficulty in exiting due to debris strewn across exit stairs can be an indirect threat to life, as can be seen in this photo following the Loma Prieta earthquake in 1989.

9.5 DAMAGE TO NONSTRUCTURAL SYSTEMS AND COMPONENTS

A lack of attention to detail during the design process is the most likely cause of damage to nonstructural systems and components in a moderate to severe earthquake. This damage poses a threat to the building occupants and may cause the owner significant losses in downtime and repairs. Examples in Table 9-1 illustrate failures in earthquakes that resulted from inadequate nonstructural design.

Nonstructural design philosophy based on the analysis and design of individual components can lead to certain nonstructural failures in moderate and severe earthquakes. The new Olive View Hospital was rendered nonoperational in the Northridge earthquake due to such a philosophy. The building was a replacement for the previous hospital that was so badly damaged structurally in the 1971 earthquake that it needed to be razed. The new replacement hospital was designed as a state-of-the-art facility, and as such, it should have remained operational during the 1994 earthquake. Figure 9-7 shows one of several systems interaction failures that caused the closure of the hospital. The building structural system supported the ceiling system and the fire sprinkler system. The codes require a component approach to seismic qualification for acceptance. The individual components that are analyzed include the ceiling, the lights set in the ceiling, the HVAC system that passes through the ceiling plane, and the main fire sprinkler feed pipe. The Olive View failure occurred when the building structure responded in one manner to the earthquake, the ceiling system and the systems that it supported shook in another manner, and finally the sprinkler system responded in a third

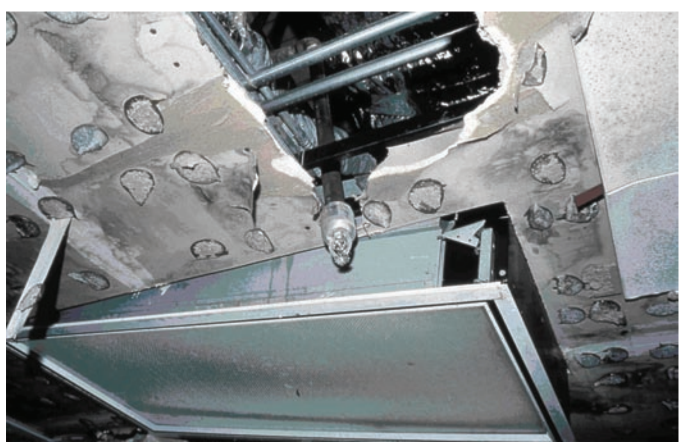


Figure 9-7

Example of systems interaction failure.

Table 9-1 Showing Example Damaged Systems/Components and Appropriate Installations

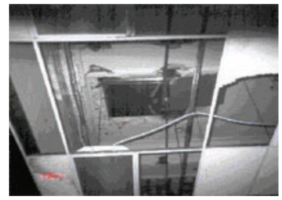
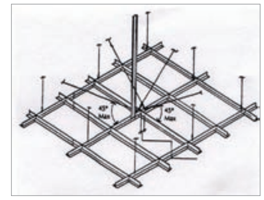
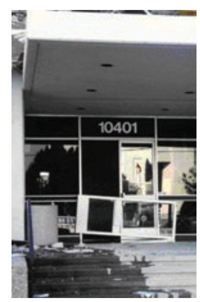
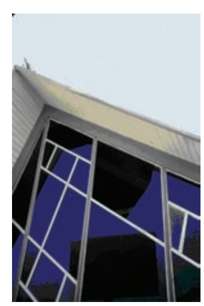
Building Element	Earthquake Damage		
Suspended Ceilings that fall may not be life threatening, but can pose exiting problems for occupants.	 Landers 1992 Dropped ceiling below structure. Note no diagonal bracing or compression posts	 Northridge 1994 New dropped ceiling below older existing ceiling. Note no diagonal bracing or compression posts.	 Appropriate Installation. Note diagonal wires and compression posts. Diagonals and compression posts are generally at 144 sq. ft.
Lighting Fixtures can be a direct threat to life, depending on the size of the fixture and the height from which it falls.	 Coalinga 1983	 Northridge 1994	 Appropriate Bracing
Doors that fail pose an obvious direct threat to life. Note the fire door in Coalinga 1983 that jammed.	 Photo by Richard Miller Santa Barbara 1978	 Coalinga 1983	 Northridge 1994
Windows could pose a direct threat to life, although more often, they are more of a cleanup hazard.	 Coalinga 1983	 Northridge 1994	 Hector Mine 1999

Table 9-1 Showing Example Damaged Systems/Components and Appropriate Installations (continued)

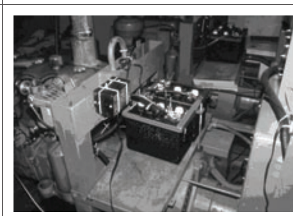
Building Element	Earthquake Damage		
HVAC Equipment can be a direct threat to life if grills/ducts fall.	 Santa Barbara 1978 Photo by Richard Miller	 Santa Barbara 1978 Photo by Richard Miller	 Northridge 1994
Kitchen Equipment can cause a direct threat to life via toppling of equipment and fire/hot liquid burns.	 Coalinga 1983	 Coalinga 1983	 Northridge 1994
Medical Equipment can cause health hazards due to spills. Recalibration is often required.	 Northridge 1994	 Northridge 1994	 Northridge 1994
Emergency Power Supplies have come a long way in the past 30 years, yet they still have difficulty operating following an earthquake.	 Joshua Tree 1992 (no failure, base isolated with snubbers)	 Northridge 1994 (no failure, hard mounted)	 Northridge 1994 (no failure)

Table 9-1 Showing Example Damaged Systems/Components and Appropriate Installations (continued)

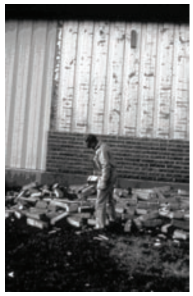
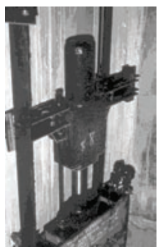
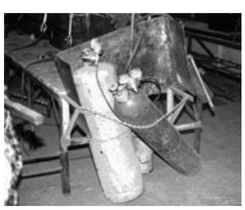
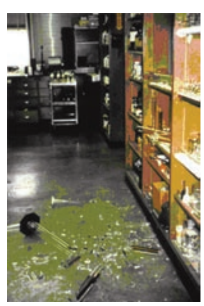
Building Element	Earthquake Damage		
Building Veneer can be a direct threat to life, especially along sidewalks.	 Loma Prieta 1989 Photo by CA DSA	 Hector Mine 1999	
Elevators should be designed to be operational following an earthquake, but shutdown is required for inspection.	 Santa Barbara 1978 Photo by Leon Stein	 Santa Barbara 1978 Photo by Leon Stein	 Santa Barbara 1978 Photo by Leon Stein
Office Furniture is often owner-supplied and not subject to seismic design by the architect.	 Santa Barbara 1978 Photo by Richard Miller	 Santa Barbara 1978 Photo by Richard Miller	 Loma Prieta 1989
Shop Equipment can pose a direct as well as indirect threat to life.	 Coalinga 1983	 Northridge 1994	 Northridge 1994 (no failure-properly anchored)

Table 9-1 Showing Example Damaged Systems/Components and Appropriate Installations (continued)

Building Element	Earthquake Damage		
Piping is especially vulnerable to breakage when it is brittle pipe, and when bending forces are applied to the threads.	 Coalinga 1983	 This pipe pounded the wall to its right. Northridge 1994	 Northridge 1994 Brittle pipe failure
Plaster and Stucco seldom will result in a hazard unless it falls from a significant height.	 Loma Prieta 1989		
Exit Ways may be blocked with debris.	 San Fernando 1971 Photo by Bill Gates	 Loma Prieta 1989	 Northridge 1994
Hazardous Materials can affect occupants and rescue workers.	 Coalinga 1983	 Whittier 1987	 Northridge 1994

manner. The result was a significant bending moment on the sprinkler drops when the ceiling impacted them, causing cross-thread bending at the joint where the drop connected to the main line. Each of the components was appropriately attached to the building as called for by the code. By not allowing either a flexible joint at the fire line drop or providing a larger hole where the sprinkler penetrates the ceiling plane, the failure of the system was virtually guaranteed.

Many of the failures found in the 1994 Northridge earthquake were a result of systems incompatibilities. It has been long realized that for building structures to survive an earthquake, there must be structural systems compatibility. Few designers would doubt the need for wall systems and roof systems to respond together in an earthquake. Yet, with respect to nonstructural considerations, the interactive nature of these systems has not been fully recognized, and thus, a $1.50 sprinkler pipe failure closed a hospital. Table 9-2 shows examples of failures and success in the design of system interactions.

Systems need to be identified and have a seismic designation and qualification program just as an individual component. Facilities with sophisticated seismic qualification programs such as the Trans-Alaska Pipeline and nuclear power plants have always looked toward qualifying the entire nonstructural systems as well as the individual components. This type of procedure is especially important where specific functions must be maintained, such as with an emergency power supply in a hospital.

Moving equipment such as reciprocating pumps need isolation so as to not interject unwanted vibrations into the building structure. This isolation needs to be “snubbed” in order to limit the lateral excursions of the equipment.

Table 9-2 Examples of Systems Interactions – Failures and Successes

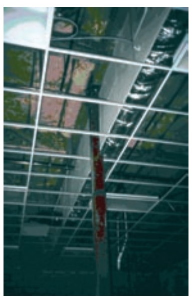
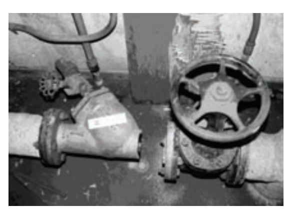
illustration	description	illustration	description
	Interaction of pendant light with glazing separating spaces in the 1994 Northridge earthquake. The pendant lights swung longitudinally, breaking the glass. Current codes require bracing of pendant lights to prevent swinging in both the transverse and longitudinal direction if they can impact other objects up to an angle of 45 degrees (1 g acceleration).		The suspended ceiling surrounding the column did not allow for ceiling movement, causing ceiling to fail at the column/ceiling interface.
	While this system was not subjected to an earthquake, it will probably suffer the same failure as seen in the photo above. This condition is increased in its complexity because of the fire separation above the suspended ceiling running diagonally from the upper right.		Vacuum System in the Coalinga Hospital that was operational following the 1983 earthquake. The tank was anchored and the flexible line to the tank prevented damage.
	Building primary structure moved in one manner, the substructure (covered walk on the right) moved differentially, causing both the HVAC duct and electrical conduit to fail in the 1994 Northridge earthquake.		While the damage to the suspended ceiling is most evident in this photo, the exterior nonstructural wall failed on this bowling alley in the 1992 Landers earthquake leaving one side of the building completely open. The failure was due to the large length of the wall that used small fasteners for anchorage to the primary structure (tapered beam).
	Building seismic separation that performed successfully in the 1978 Santa Barbara earthquake. The cosmetic trim panel was damaged, as expected. Photo by Richard Miller		Bringing large utility lines into a building that is base isolated requires consideration of systems interaction. Here, the water line has a braided section to allow for differential movement between the building and the utility line.

Table 9-2 Examples of Systems Interactions – Failures and Successes (continued)

illustration	description	illustration	description
	This ceiling displaced and caused the water supply line that passed through the ceiling to bend and break the threads in the pipe above the ceiling during the earthquake. Water leaked for some time into the ceiling cavity following the 1994 Northridge earthquake, finally causing a collapse of the hard ceiling and the glue-on panels, months after the earthquake.		The rectangular building configuration of this library had stiff side walls and a relatively stiff rear wall. The large expanse of glass on the front wall allowed for excessive torsional movements in the 1983 Coalinga earthquake. The larger upper story window panes broke. As a general rule, smaller window panes perform better in earthquakes.
	The diagonal member running from the top left was a horizontal, nonstructural architectural appendage that separated the buildings on the left from the buildings on the right. When the garage spaces on each building failed in the 1994 Northridge earthquake, they in turn caused the failure by collapse of the architectural appendage and blockage of the access between the buildings. Emergency vehicles were unable to enter the space between the buildings due to the collapse of this nonstructural appendage.		Ceiling tiled popped out of this suspended ceiling during the 1992 Landers earthquake due to the high bay, large suspension length below the structure and a lack of compression posts to prevent the ceiling from lifting in a wave like fashion during the earthquake. Adding to the failure of this ceiling was poor workmanship at the ceiling grid joints.
			This cast-iron brittle pipe entered the utility room through the stiff concrete slab on the right and exited the room through a one-hour fire wall to the left. The rigid nature of the two connections on either side of the valve caused its failure in the 1994 Northridge earthquake.

9.6 DESIGN DETAILS FOR NONSTRUCTURAL DAMAGE REDUCTION

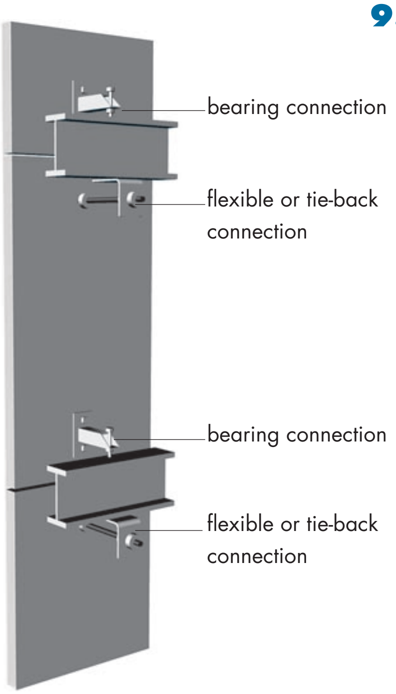


Figure 9-8: Typical push-pull connection for precast panel.

This section shows some examples of conceptual details for a number of typical nonstructural components. These are intended to give an indication of appropriate design approaches and should not be used as construction documentation. It will be seen that these approaches mostly consist of providing adequate support and supplementary lateral bracing, or isolating nonstructural components from the building structure to reduce undesirable interaction between nonstructural and structural elements. The isolation issue is discussed in more detail in Section 9.7

9.6.1 Precast Concrete Cladding Panels

Figure 9-8 shows a typical "push-pull" connection for a precast panel that spans between floors. The bottom connection provides bearing; the top connection uses a steel rod that is designed to bend under lateral drift. The rod must be strong enough, however, to resist out-of-plane wind loads. The bearing connections may also be located at the top and the flexible connection at the bottom.

Figure 9-9 shows a typical layout of the supports for a story height panel and spandrel panels, and diagrams the lateral structural movement that must be accommodated.

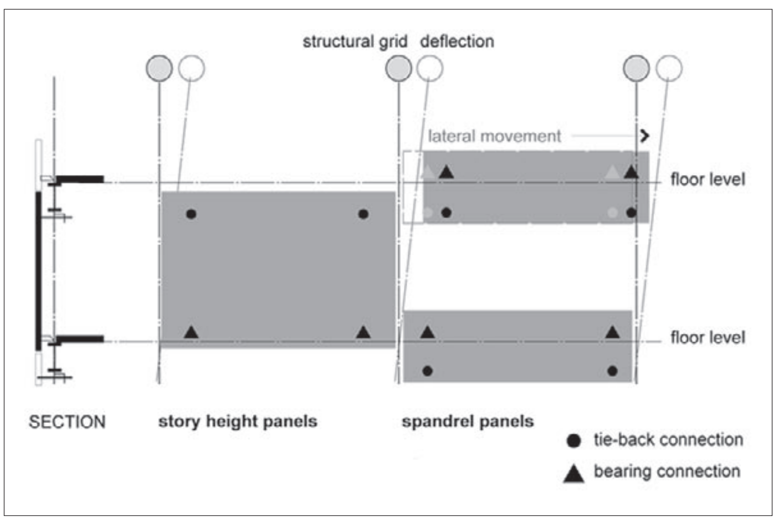


Figure 9-9: Connection types and locations for precast panels.

9.6.2 Suspended Ceilings

Figure 9-10 shows typical suspended-ceiling bracing. Diagonal bracing by wires or rigid members: spacing should not be more than 144 sq. ft. The vertical strut is recommended for large ceiling areas in high seismic zones; it may be provided by a piece of metal conduit or angle section.

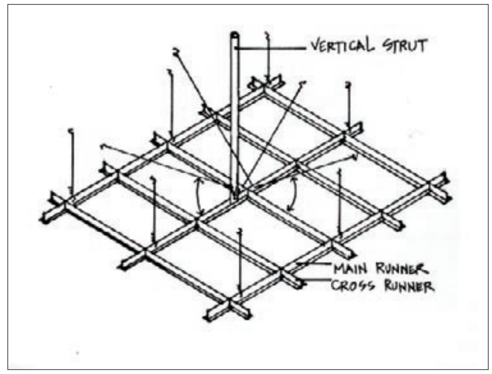


Figure 9-10: Suspended-ceiling seismic bracing.

9.6.3 Lighting Fixtures

Heavy fluorescent light fixtures inserted in suspended ceilings must be supported independently, so that if the grid fails, the fixture will not fall. Figure 9-11 shows a lighting fixture with two safety wires located at the diagonal. For heavy fixtures, four wires must be provided. Suspended fixtures must be free to swing without hitting adjoining components.

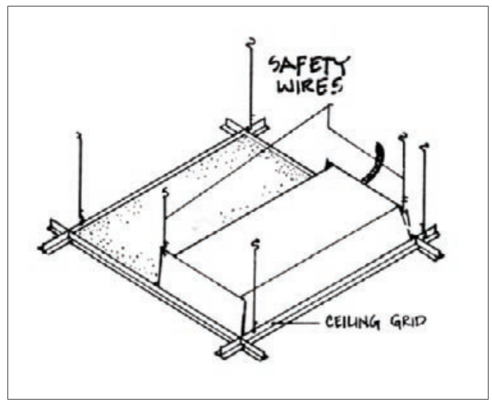
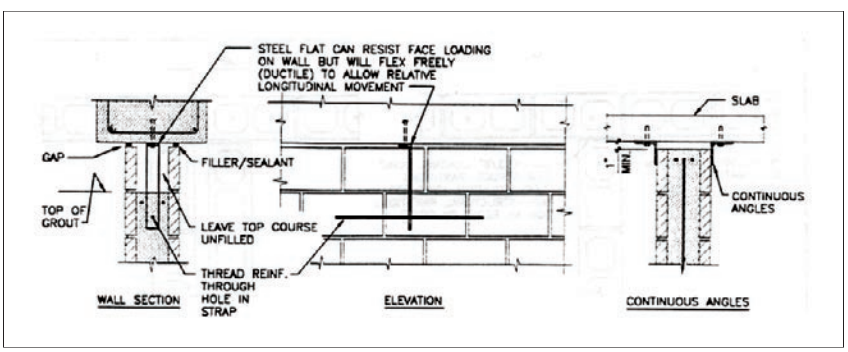


Figure 9-11: Safety wire locations for fixture supported by suspended-ceiling grid.

9.6.4 Heavy (Masonry) Full-Height Non load Bearing Walls

Heavy partitions, such as concrete block, should be separated from surrounding structure to avoid local stiffening of the structure and to avoid transmitting racking forces into the wall. Figure 9-12 shows two approaches for providing sliding or ductile connections at the head of full-story masonry partitions.

Figure 9-12: Attachment for full-height masonry partition wall that allows relative longitudinal movement (EQE).



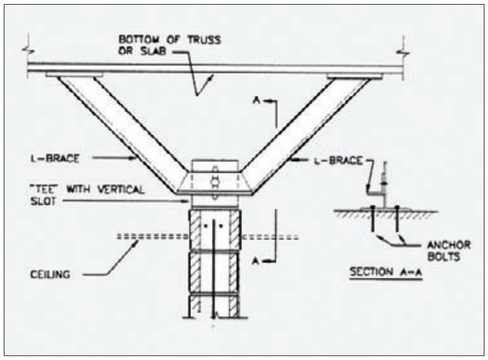


Figure 9-13: Seismic bracing for masonry partial height partition wall (EQE).

9.6.5 Partial–Height Masonry Walls

Figure 9-13 shows an overhead bracing system for a partial height wall. The bracing used should have some degree of lateral flexibility so that structural deflections parallel to the wall do not transmit forces into the system. Where vertical deflections due to dead loads, live loads, and seismic forces could occur, a slotted hole as shown, or some similar provision, should be made to prevent vertical loading of the wall.

9.6.6 Partial-Height Metal Stud Walls

Metal stud partitions that terminate at a suspended ceiling should be braced independently to the building structure, as shown in Figure 9-14. Normal office height partitions can be braced by a single diagonal angle or stud brace.

9.6.7 Parapet Bracing

Heavy parapets should be braced back to the roof structure. This is a typical problem with unreinforced masonry buildings, which often have large unsupported parapets. Figure 9-15 shows bracing for an existing masonry parapet; the roof structure should also be securely tied to the wall (not shown).

Figure 9-14: Bracing for partial height stud wall (EQE).

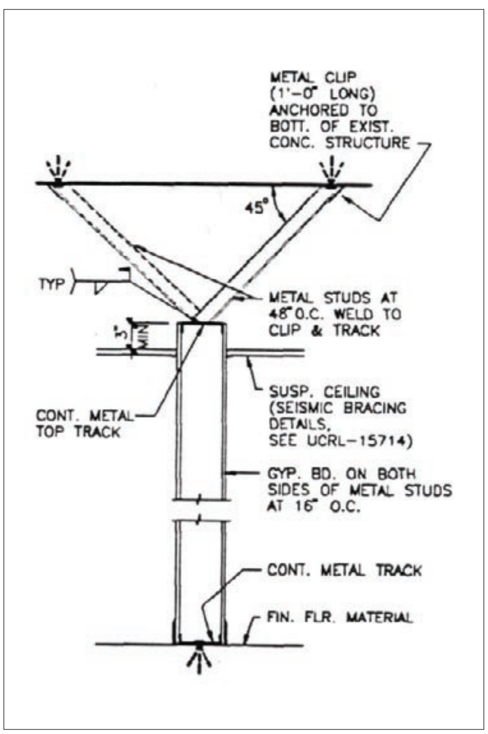
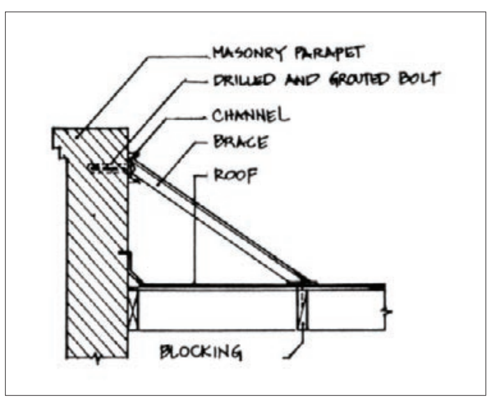


Figure 9-15: Bracing for existing unreinforced masonry parapet.



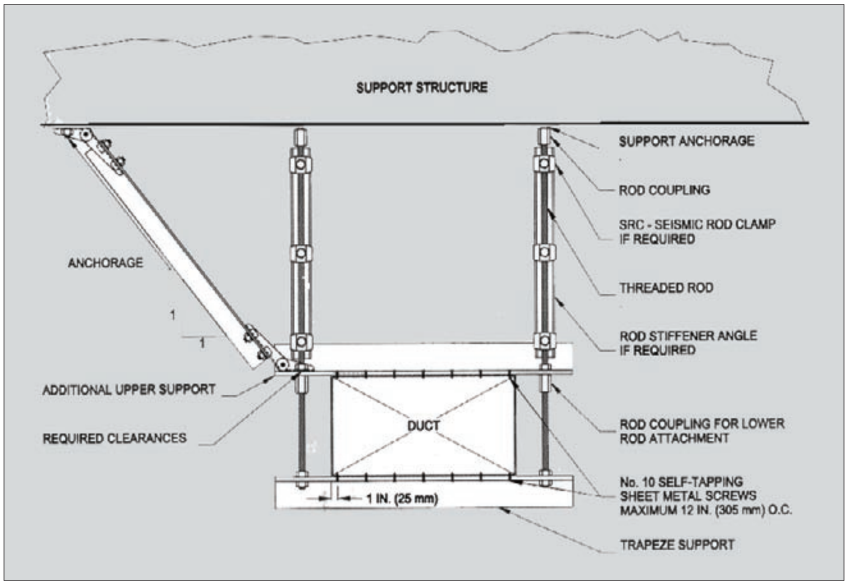


Figure 9-16:

Typical duct bracing system (Mason Industries Inc).

9.6.8 Sheet Metal Ductwork

Figure 9-16 shows a typical support and bracing system for large duct-work in a high seismic zone. The seismic code specifies the size of ducts and length of support that require seismic bracing.

9.6.9 Piping

Figure 9-17 shows typical bracing for large diameter piping. The seismic code specifies the types and diameter of piping, and length and type of hanger, that require seismic bracing.

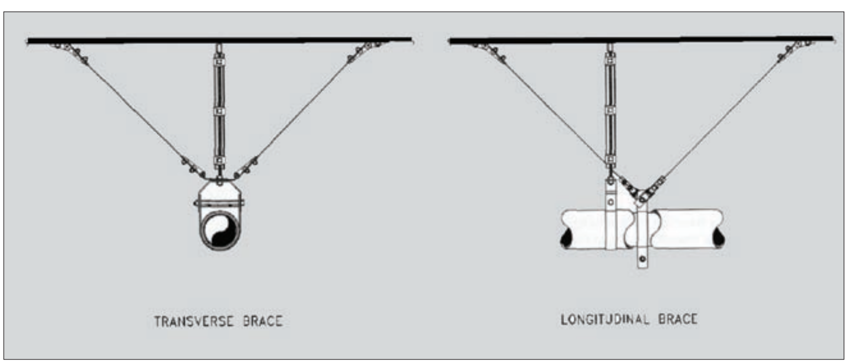


Figure 9-17:

Typical bracing for piping (Mason Industries Inc).

9.6.10 Vibration-Isolated Equipment

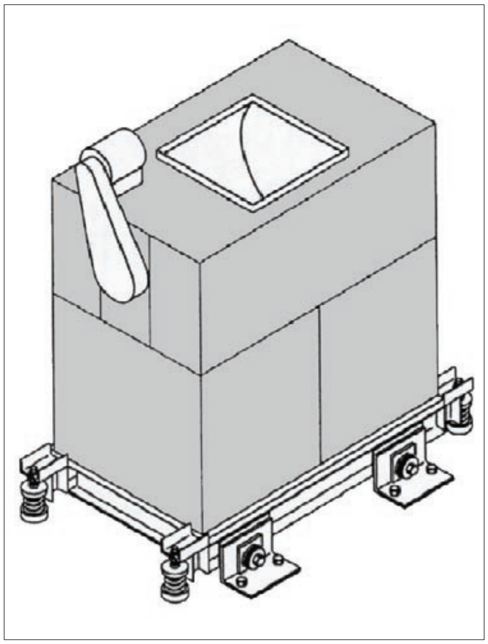


Figure 9-18: Vibration-isolated chiller with snubbers to restrict lateral movement (Mason Industries Inc).

Equipment mounted on spring vibration isolators needs to be fitted with "snubbers" that limit lateral motion to prevent the equipment toppling off the isolators and suffering damage (Figure 9-18). The frequency of the isolation system is usually such that the motion of the equipment is greatly increased by earthquake forces. The snubbers are faced with resilient material that cushions any impacts that may occur. Detailed guidelines for the design of seismic restraints for mechanical, electrical, and duct and pipe are in FEMA publications 412, 413 and 414.

9.6.11 Emergency Power Equipment

Batteries for emergency power need positive restraint. Figure 9-19 shows a custom designed rack, constructed from steel sections, to support and restrain a set of batteries. The batteries are also strapped to the rack for positive restraint. Alternative emergency power sources, such as gas or oil, need flexible utility connections and restrained equipment.

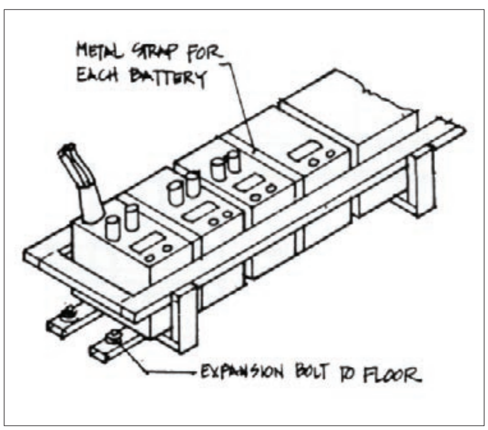


Figure 9-19: Emergency power battery rack support.

9.6.12 Tall Shelving

Tall shelves, such as library shelves, are often heavily loaded and acceleration sensitive. They need longitudinal bracing and attachment to the floor. The top bracing should be attached to the building structure and strong enough to resist buckling when the heavy shelves attempt to overturn (Figure 9-20).

9.6.13 Gas Water Heaters

Gas water heaters need restraint to prevent the heater tank from toppling and breaking the gas connection, causing a fire risk. Figure 9-21 shows a domestic hot water heater installation. A flexible gas connection is desirable but not essential if the tank is well restrained. The bottom restraint can be provided by an additional strap, or by securely bolting the base support to the floor.

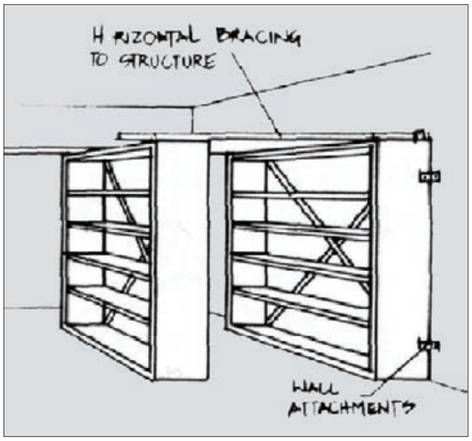


Figure 9-20: Typical layout of bracing for tall shelving.

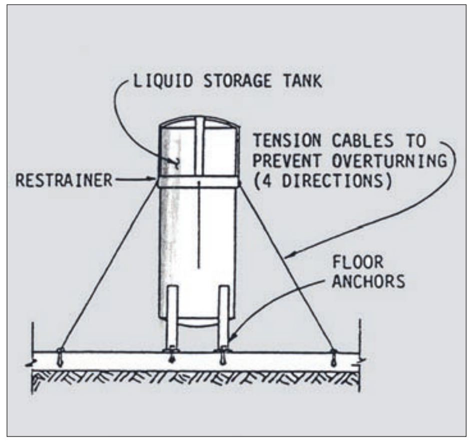


Figure 9-21: Anchorage of free-standing upright liquid storage tank.
SOURCE: EQE.

9.7 THE NEED FOR SYSTEMS DESIGN

Following a damaging earthquake, whether large or small, the public expects to be able continue to use many building types. The building types that have the mandate for some post-earthquake operation tend to be essential facilities, such as acute care hospitals and those buildings where the owners see a clear financial benefit for continued operation. Unfortunately, the expectations of the performance of our essential facilities are often not realized, and a number of modern healthcare facilities close with all too much regularity following even moderate earthquakes.

Over the years, codes have become more and more sophisticated with respect to structural seismic integrity. Unfortunately, there remains a lack of understanding by many with respect to building function, in which the nonstructural systems play the key role. The philosophy of code implementation carried out via the model codes, including the *International Building Code* (IBC), is based on the seismic provisions developed in the National Earthquake Hazard Reduction Program (NEHRP) and the *Uniform Building Code* (UBC), which uses the Structural Engineers Association of California recommendations. Both require simple component anchorage, which does not address function to the necessary level, especially for essential facilities.

Other design professions outside the building industry have long recognized that there is a need for systems design when continued function is necessary. The practice of systems design can be witnessed in aerospace design, naval design, nuclear power design, weapons design, and even race car design. As an example, few would accept rides on modern aircraft if it was not believed that the aircraft had been designed from a systems engineering point of view. It would not be acceptable for the landing gear to pinch the hydraulic brake lines when the wheels fold into the fuselage.

Systems failures in health care facilities throughout the impacted area in the Northridge earthquake prompted the California Seismic Safety Commission to sponsor Senator Alfred Alquist's Hospital Seismic Safety Act of 1994. This legislation was clear in its direction to the industry and design professionals to maintain the operability of health care facilities following future damaging earthquakes. The legislation called for consideration of systems design. Hospitals and other essential facilities complying with the legislation will have a lower risk of failure in future earthquakes.

The California Hospital Seismic Safety Act of 1994 took the further step of identifying building contents within the design parameters. Prior to the implementation of this legislation, building contents had been left out of the qualification procedures in almost all codes, unless they met certain criteria. Without consideration of building contents, hospitals continue to be more vulnerable to failure due to earthquake shaking.

9.8 WHO IS RESPONSIBLE FOR DESIGN?

There is no clear answer for the responsibility of many nonstructural design issues. In order to help designers determine who is responsible for nonstructural issues for both systems and components, Table 9-3 is provided as a guide. Architects may wish to use this as a guide in establishing contractual relationships with their consultants prior to beginning design. It is certainly helpful to all design professionals to know who is responsible for specific tasks. It should be noted that there are many cases where design responsibilities are not clear, even when a responsibility chart such as that below is used. The architect, as the design professional in charge, must ensure that the assigned responsibilities are clearly defined.

Table 9-3 Design Responsibilities for Nonstructural Components

The following list can be reviewed and modified by architects for their specific project. The table is not intended to apply to every project, but rather to act as a check list and a guide.

Nonstructual System or Component	Architect	Structural Engineer	Electrical Engineer	Mechanical Engineer	other design professionals	Remarks
curtain wall	1	2			consider a specialty consultant	Small glazing panes perform better in earthquakes. Avoid window film unless properly applied.
doors / windows	1					Consider how doors will avoid racking in nonstructural walls.
access floors	1				consider a specialty consultant	Consider in-the-floor ducts rather than raised floors where practical
HVAC systems	2			1		Systems that require vibration isolation also require snubbing.
plumbing systems	2			2		Vertical plumbing runs are subject to floor to floor drift
communication systems	2		1		1 consider a specialty consultant	Some communications systems come as a package. Make sure that they interface with the building appropriately.
data systems	2		1		1 consider a specialty consultant	Consider support systems such as cooling environments.
elevator systems	1	2	2	2	2	Design some elevators to operate after the earthquake
emergency power supply system	2	2	1	2	2	All systems interfaces need to be considered as their vulnerability can cause an entire facility to become non-operational.
fire protection systems	2		2	1	1 consider a specialty consultant	Floor to floor piping is subject to story drift.
kitchen systems	1				2 consider a specialty consultant	
lighting systems	2		1			

Table 9-3 Design Responsibilities for Nonstructural Components (continued)

Nonstructual System or Component	**Architect**	**Structural Engineer**	**Electrical Engineer**	**Mechanical Engineer**	**other design professionals**	**Remarks**
medical sytems	1	2	2	2	[consider a specialty consultant	Often, the architect needs to provide protection to equipment as it is outside the code requirements.
ceiling systems	1	2	2	2		Avoid drop ceiling elevation changes. Avoid Large ceiling cavities.
unbraced walls and parapets	1	2				
interior bearing walls	1	2				
interior non-bearing walls	1					Consider earthquake effects on doors for egress.
prefabricated elements (architectural appendages)	1	2				
chimneys	1	2				
signs	1	2				
billboards	2	1	2		2 consider a specialty consultant	
storage racks	1				2 consider a specialty consultant	Proprietary manufactured racks may or may not include seismic design considerations.
cabinets and book stacks	1				2	Architect needs to provide proper wall backing.
wall hung cabinets	1			1		Architect needs to provide proper wall backing.
tanks and vessels	2	2				
electrical equipment	2	2	1			
plumbing equipment	2	2		1		

Note: 1 = Primary Responsibility 2 = Support Responsibility

9.9 NONSTRUCTURAL CODES

The early 1970s saw the first inclusion for nonstructural provisions other than walls, parapets, and chimneys. The provisions have grown to include a wide variety of nonstructural components and building systems since the mid-1970s, but the seismic codes have yet to recognize the need for qualification of owner-supplied equipment that is not fixed to the building. The codes have also yet to come to grips with systems qualification and continued performance for facilities. A discussion of the philosophy of codes for nonstructural components and systems is presented in Chapter 6, Section 6.6.

9.10 METHODS OF SEISMIC QUALIFICATION

Qualification involves the acceptance of components and systems for use in a seismic environment and compliance with code requirements. There are numerous methods by which seismic qualification can be realized. Each method has a narrow window of applications for effective seismic qualification. These are:

- Design Team Judgment
- Prior Qualification
- Physical Tests
- Mathematical Analysis
- Static Equivalent Analysis
- Dynamic Analysis

9.10.1 Design Team Judgment

Design team judgment is a valuable resource in any seismic qualification program. An inappropriate selection of equipment or qualification method by the design team may lead to nonstructural system failures during an earthquake. The design team needs to meet early in the programming, schematic, and design development phases to discuss the various systems to be used in a facility design. Just as in preliminary design the architect is interested in how deep structural members need to be for floor spans, and how much room is needed above the finished ceiling and below the structural system for HVAC and lighting, the architect and engineers need to discuss how movement of the various systems will impact each other in a sizeable earthquake. Early appropriate building configuration decisions by the design team will have a great impact on the success of a building structure in an earthquake. Similar appropriate decisions by the design team early in the design process will have a profound impact on the design of nonstructural systems and components. Following the early discussions of the design team, more quantitative methods of qualification can be utilized, as discussed in the following sections.

9.10.2 Prior Qualification

In some cases, a product or system can be shown to have a previous qualification procedure that exceeds the code requirements. This might include equipment that has been designed for shipboard installation, where the accelerations expected and durations of those accelerations far exceed the code requirements of a simple static mathematical model. Such equipment is arguably considered to be qualified by prior experience. Other examples might include a component manufacturer that has had their equipment tested on seismic shaking equipment that provides a stringent-enough test to envelope the specific installation, providing a prior qualification. When available, the manufacturers will provide test results and/or reports detailing the testing program for the building official's review.

Appropriate detailing employing prior qualification is often used by the architect. Consider, for example, suspended ceiling systems. Most architects use suspended ceiling details that have proven over time to be effective, either through prior seismic experience or prior analysis. The familiar 45° splay wires at areas of interval, such as 144 sq. ft., are such an example. There is no need for the architect to recalculate the forces in the resisting wires for each new application. Choosing the appropriate detail is often sufficient. There are, however, limits on "standard details", and the architect should always review each detail to be used for the specific application.

9.10.3 Mathematical Analysis and Other Qualification Methods

There are two basic forms of analysis. The first is a simple static equivalent analysis. This is the method most suited for most simple architectural problems for nonstructural design. The second is the more complex dynamic analysis which requires costly engineering analysis and is seldom used for nonstructural components. In place of, or in combination with, physical testing the latter may be used.

These methods of qualification are generally not going to be employed by architects in "normal" designs. In general, they are better suited for product/system manufacturers and researchers that want to show either a wide range of possible applications or to confirm predicted responses. All of these qualification methods are expensive and time consuming.

9.11 SOME MYTHS REGARDING NONSTRUCTURAL DESIGN

● "My Engineers take care of all my seismic design"

Many architects believe that seismic design is controlled in total by their engineers and they should not be involved in the conceptualization or the coordination of seismic design. As discussed throughout this work by the various authors, successful seismic design begins and ends with the architect. It is true that the engineers may control the details of many components within the facility, but it is the architect who must understand the interrelationship between the various systems within the facility for successful performance during and after an earthquake.

● "My building is base isolated … I don't need to worry about the nonstructural components"

Building base isolation in general reduces the effects of horizontal motions within a building, but it does not eliminate them. The architect and design team should be aware of the limitations of base isolation and special conditions, such as the need for utilities to accommodate large lateral movement where they enter the building above or below ground.

● "Window films protect windows from breakage in an earthquake"

If properly applied, window films can reduce some glass breakage. The film needs to be taken all the way to the edge of the glass. Often film to be applied to the glazing, while it is mounted in its frame, and is then cut with a razor blade against the mullions and muttons that score the glass, making it vulnerable to breakage during violent shaking. As the

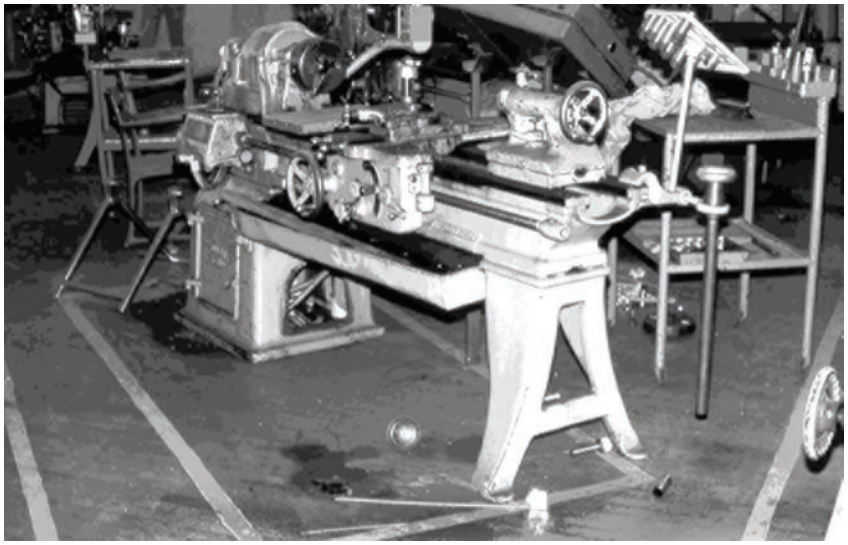


Figure 9-22: This lathe lifted up in the air and came down about four inches from its starting point before sliding another six inches, where it finally came to rest in the 1983 Coalinga earthquake. The initial complete lifting off the floor is evidence of vertical acceleration of more than 1g.

film ages, it can lose its adhesion characteristics. If films are used, they should be cross-ply films and have undergone aging tests to predict how they will outgas and to what extent they will become brittle.

- ### "My building in San Bernardino survived the 1994 Northridge earthquake … it is earthquake proof"

San Bernardino (or any other appropriate location) was a long distance from the 1994 Northridge earthquake. While distance does not always guarantee safety (San Francisco was approximately 60 miles from the focus of the Loma Prieta earthquake), in general being a substantial distance from the earthquake will lessen the effects of the earthquake on the building and its nonstructural components. Nonstructural failures are commonly seen at greater distances than structural failures. This is especially the case where the building components are not designed for the earthquake environment.

- "Vertical motions in earthquakes do not need to be considered for nonstructural design"

Historically, the model earthquake codes paid little attention to the vertical component of shaking generated by earthquakes. As a rule of thumb, the maximum vertical ground motion is generally 60 to 70% of the maximum horizontal ground motion. While it may be unnecessary to consider the vertical motions of the structure as a whole, this is often not the case with nonstructural design. The model codes have little reference to vertical acceleration design requirements for nonstructural components. The building, usually due to its architectural configuration, can act as an amplifier for both horizontal and vertical motions. Therefore, even though the code most often does not require vertical design resistance, the designer must be cognizant of the implications of vertical motions during an earthquake and their potential effects (Figure 9-22).

9.12 WHAT CAN THE ARCHITECT DO TO DECREASE NONSTRUCTURAL DAMAGE?

Not only does the architect have the obligation to coordinate the overall design of the building, but the architect is also responsible for the basic seismic safety of the design.

The architect should guide the other design professionals in the design decisions, rather than simply turning the design over to the project engineers. Since many nonstructural issues involve the intermixing of several engineering professions, the architect should understand how each system will react with the other building systems. The architect needs to be able to visualize the system, its components, and how they will interact in an earthquake, strong winds, fire, etc. The architect should sit down with the consulting engineers early and often, beginning with a discussion of the earthquake performance objectives for the facility, to permit each of the disciplines to see the potential for interactions between systems and components. Office standards should be developed for the interfacing of systems and components.

Simple designs make design life easier. The current vogue for complex shapes in architectural design increase the complexity of the nonstructural systems. This increase in complexity decreases the architect's ability to visualize how systems and components will respond and interact.

9.13 THE COMPLEXITY OF RETROFITTING EXISTING BUILDINGS

The nonstructural implications of retrofitting existing buildings can be very complex. In many cases, the structural seismic retrofit may be compromised due to historic codes or other considerations. In some cases, buildings have grown over time, which often means that nonstructural systems pass through more than one time era of construction. These interfaces may make the nonstructural retrofit very difficult. California architects and engineers are faced with a particular difficulty in this issue, based on the 1994 law requiring the upgrading of all existing acute care hospitals by 2030 (SB1953). In fact, the task may be essentially impossible, and following the expense of the retrofits, hospitals may yet run a high risk of seismic failure due to nonstructural systems/component failures.

A better solution than expecting performance out of systems that are difficult if not impossible to retrofit might be a “hospital lifeboat”. The lifeboats could be self-contained, factory-built modular buildings sized to accommodate the expected emergency population needing attention following a major earthquake. The lifeboats would be permanently stationed on the health care campus, ready for operation as needed. These lifeboats could be provided at a fraction of the cost of the thorough retrofits currently required by SB1953, saving California money and providing a much higher degree of confidence that the hospitals will be operational for emergency services following an earthquake.

For facility types other than acute care facilities, the design team needs to identify how the existing building will react to the new structural improvements, and how these will impact the nonstructural elements of the facility. The design professional may be required to determine which systems/components can fail and simply protect the occupants from falling hazards.

9.14 CONCLUSIONS

The largest immediate strides in resisting the impacts of nonstructural failures in future earthquakes will come from designers who understand the implications of systems design. Next, there will be great increases in nonstructural seismic resistance by designers implementing the keep-it-simple philosophy. Apart from that, there will be great strides in structural systems that will result in reduced-motion inputs at the nonstructural system/component interfaces. These include base isolation as it is currently being employed. Another future structural improvement that will likely improve nonstructural seismic performance is the increasing use of both active and passive seismic dampers. These systems show promise for significantly decreasing building motions that in turn will decrease nonstructural damage. Some active dampers under development will be able to respond to the earthquake in almost real time.

On the distant horizon is the transformation of the building structure from its seemingly rigid skeleton to a skeleton with a muscle system similar to an organism. Shape-memory materials such as nitinol can be fabricated to act like muscles. The nitinol reduces its size when heated, rather than expanding like most construction materials. These "building muscles" can then be either tightened or relaxed with electrical input (heat), so that the building achieves "balance" during a seismic event in much the same way that our bodies can remain balanced when we stand on a moving bus or train. As these shape-memory materials reduce the effects of acceleration on the building as a whole, they will reduce the large acceleration inputs on the nonstructural systems/components. Shape-memory construction has been successfully utilized in aerospace design in recent years. It will take considerable time for it to be successfully used in building design, although some limited research has been reported.

9.15 REFERENCES

2001. *California Building Code* based on the 1997 *Uniform Building Code*, International Conference of Building Officials, Whittier, CA.

2003 *International Building Code*, International Code Council, Country Club Hills, IL

FEMA 74, *Reducing Risks of Nonstructural Earthquake Damage*, FEMA, Washington D.C. 1994.

EQE, *Structural Concepts and Details for Seismic Design*, Lawrence Livermore National Laboratory, Livermore, CA. 1991.

Mason Industries Inc., *Seismic Restraint Guidelines*, Mason Industries Inc, Hauppauge, NY. 1999.