Seismic Protection of Plumbing Systems

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Every structure is designed for vertical, or gravity, loads. In the case of pipes, gravity loads include the weight of the pipe and its contents, and the direction of the loading is downward. Seismic loads are the lateral forces exerted on a structure during an earthquake, and earthquake forces can be in any direction. The ordinary supports designed for gravity loads generally compensate for vertical loads during an earthquake. Therefore, the primary emphasis in seismic design is on lateral, or horizontal, forces.

Study of seismic risk maps indicates that the potential for damaging earthquake motion is far more pervasive than commonly known. Complete seismic design requirements, including the construction of nonstructural elements, are in effect in only a small fraction of the areas that could be rated as having a high or moderate risk. Nonstructural components and elements such as piping, water heaters, pumps, tanks, boilers, ductwork, and conduit are partitioned into two categories: attached to a building and not attached to a building. Seismic design requirements for nonstructural elements, except for heavy cladding panels, are seldom enforced even in California, which is considered the innovator in state building code requirements related to seismic movement. However, nonstructural damage resulting from small earthquakes shows that the major advancements in building structural design by themselves may not have produced an acceptable level of overall seismic protection.

Now that the potential for collapse or other direct, life-endangering structural behavior is quite small, at least for modern structures designed and built in accordance with current seismic codes, attention has shifted to nonstructural life-safety hazards, continued functionality, and economic issues. The cost of an interruption in a building's ability to function, which could cause a loss of rent, disruption of normal business affairs, or curtailment of production, is coming more into focus.

The primary codes governing the seismic laws are found in the International Building Code (Chapter 16). However, this code refers to ASCE/SEI 7: *Minimum Design Loads for Buildings and Other Structures*. This book subdivides the issues as follows:

- Chapter 12: Building Structures
- Chapter 13: Nonstructural Components
- Chapter 15: Non-Building Structures
- Chapter 17: Seismically Isolated Structures
- Chapter 18: Structures with Damping Systems

Chapters 13 and 15 are most relevant to the plumbing engineer. Nonstructural components include mechanical, electrical, and architectural elements. If the components are not attached to the building or on slab, then they can be considered non-building structures. The level of hazard to the building is defined as maximum considered earthquake (MCE) ground motion. The acceleration from this motion times the effective mass of the component is the effective seismic force acted on the mass.

The costs of seismic protection of plumbing components and equipment range from small, such as those to anchor small tanks, to a considerable percentage of installation costs, such as those for complete pipe-bracing systems. Beyond protection of life, the purpose or cost/benefit relationship of seismic protection must be clearly understood before the appropriate response to the risk can be made. The design professional responsible for any given element or system in a building is in the best position to provide that response. Seldom, however, can rational seismic protection be supplied solely by a single discipline. Building systems are interdependent in both design and function, and good seismic protection, like good overall building design, is best provided by employing a cooperative, interdisciplinary approach.

This chapter is intended to provide a basic understanding of the mechanisms of seismic damage and the particular vulnerabilities of plumbing systems and equipment. The design professional should sufficiently understand the problem to select the appropriate seismic protection in any situation based on a ranking of the susceptibility of damage and a knowledge of the scope of mitigation techniques. The seismic protection techniques currently in use for buildings are described in general. Although specific seismic protection details for some situations are discussed, it is suggested that structural design assistance be obtained from a professional of that discipline. Care should be taken in the design of seismic control systems. Proper design may require assistance from an engineer experienced in these systems. In all cases, the current local building code requirements for seismic movement should be consulted and used as the minimum standard. The detailed analysis and design techniques used for nuclear power plants and other heavy industrial applications, while similar in nature to those discussed here, are considered inappropriate for most buildings and are beyond the scope of this chapter. References are given throughout the text for additional study in specific areas of interest.

SEISMIC PROTECTION TECHNIQUES FOR EQUIPMENT

Assuming that the building in which the piping systems are supported is designed to perform safely in response to earthquake forces, the piping systems must be designed to resist the seismic forces through the strength of the building attachments.

The design professional must consider local, state, and federal seismic requirements, as applicable, in the area of consideration. Only those engineers with seismic experience should design the supports required for seismic zones. Close coordination with the structural engineer is required to ensure that the structural system properly supports the mechanical systems and equipment.

Seismic protection of equipment in buildings, as controlled by the design professional, consists of preventing excessive movement that would either damage the equipment directly or break the connected services. Equipment certification is required in the International Building Code for equipment with an importance factor of 1.5. Importance factors vary from 1.0 (basic commercial building) to 1.5 (hospitals). Piping systems with an importance factor of 1.5 must be completely designed and detailed on the plans, including supports and restraints.

Other than meeting the requirements set forth in the International Building Code, the ability of the equipment housing or working parts to withstand earthquake vibration generally is not considered for one or more of the following reasons:

- Such failure would not endanger life.
- Continued functioning is not always required.
- Most equipment will experience transportation shocks or working vibrations that are similar to earthquake motions, and the housing and internal parts therefore are considered adequate.
- The design professional has little control over the manufacturing process. Competitively priced equipment specially qualified to resist earthquake motion is not available.
- Because of a lack of performance data for equipment that is anchored, the extent of the problem is unknown.

Movement to be prevented is essentially overturning and sliding, although these effects can take place with a variety of characteristics:

- Overturning (moment): Overturn of equipment; failure in tension or compression of perimeter legs, vibration isolators, hangers, or their supports; excessive foundation rotation
- Sliding (shear): Sliding of floor-mounted equipment; swinging of hung equipment; excessive sideways failure of legs, stands, tank mounts, vibration isolators, or other supports. (Although these failures often are described as local overturning of the support structure, they are categorized as a shear or sliding failure because they are caused by the straight lateral movement of the equipment rather than the tendency to overturn.)

The prevention of overturning and sliding effects is best discussed by considering the categories of mounting equipment, such as fixed or vibration isolated and floor mounted or hung.

Fixed, Floor-Mounted Equipment

This group includes tanks, water heaters, boilers, and other equipment that can rest directly on the floor. Although anchoring the base of such equipment to the floor is obvious, simple, and inexpensive, it often is omitted. Universal base anchorage of equipment undoubtedly would be the single largest improvement and would yield the largest cost/benefit ratio in the entire field of seismic protection of plumbing equipment. This anchoring is almost always to concrete and is accomplished by cast-in-place anchor bolts or other inserts or by drilled or shot-in concrete anchors. The connection to the equipment base depends on the configuration and may require angles or other hardware to supplement the manufactured base. For elements that have a high center of gravity, it may be most efficient to prevent overturning by bracing at the top, diagonally down to the floor, to the structure above, or to adjacent structural walls. Vertical steel beams, or strongbacks, also can be added on either side of tall equipment to span from floor to floor. A vertical slip joint connection should be placed at the top of such beams to avoid unexpected interaction between the floor structures.

Tanks supported on cast iron legs or threaded pipes have proven to be particularly susceptible to support failure. These types of legs should be avoided or should have supplemental bracing.

The horizontal earthquake loads from equipment mounted on or within concrete stands or steel frames should be braced from the equipment through the support structure and out the base. Concrete tank saddles often are not attached to the tank, are of inadequate strength (particularly in the longitudinal direction), are not anchored to the floor foundation, or have inadequate provisions for earthquake-generated forces in the floor or foundation. Steel equipment frames often have similar problems, some of which can be solved by diagonal bracing between the legs.

Domestic water heaters require special attention for several reasons. Most water heaters are tall and slender, thus providing a high center of gravity. In a seismic event, the tendency is for the water heater to tip over. The small feet that support many water heaters have been known to collapse under the stress of seismic motion, potentially further throwing the unit off balance. Many units are elevated on small platforms and can dance right off the edge if unbraced. The resulting excessive movement or tipping of the water heater can rupture the water piping and fuel gas piping, potentially resulting in fire or water damage or even complete destruction of a home that might otherwise have been relatively untouched by the earthquake. Thus, the point to anchoring a water heater is to protect life and property by preventing the fire or water damage that can result if the unit gets thrown about or tipped over. Anchoring the unit to a wall or other secure structure is an inexpensive and usually uncomplicated bit of insurance. At the same time, it is advisable to replace rigid fuel gas and water connectors with flexible ones to minimize the risk of even a small tremor breaking a line.

Although usually thought of as an earthquake issue, protection of the water heater is also a good idea as a general home security measure. Other natural events, such as hurricanes or tornadoes, can cause structures to move, and even a careless late-night parking bump could be enough to start a garage fire. In the event of any kind of natural disaster or civil defense situation, the water heater is a significant source of critical fresh water that is well worth protecting.

Code requirements for bracing or anchoring water heaters have been in place since the early 1980s. Initially, the Uniform Plumbing Code (UPC) supplied no specifics as to how to accomplish this or how many anchors to use. Later, the UPC was revised to require two points of anchorage in the upper and lower thirds of the heater, which remains true today (UPC Section 508.2). Both the UPC and the International Plumbing Code (IPC) specify that a water heater shall be strapped within the upper third and lower third of its vertical dimensions. The UPC additionally requires that at the lower point, a minimum distance of 4 inches (101.6 mm) shall be maintained above the controls with the strapping. The IPC and the International Mechanical Code (IMC) point to the International Residential Code (IRC) for this directive. Because of the availability of low-cost pre-manufactured kits, this approach is becoming universal wherever water heater bracing is required. Some pre-manufactured kits have straps that wrap completely around the water heater, while others go from one side to the other.

Regardless of the plumbing code, structural engineering calculations and details may be required for any plumbing equipment or piping. The calculations depend on all factors related to the seismic behavior, soil, type of building, location of the equipment relative to the ground level, and type of attachments. The attachment detail becomes more critical when the forces are being transferred back to the building.

The following plumbing nonstructural components are exempt from seismic calculations (ASCE/SEI 7-10 Section 13.1.4):

- All plumbing components in Seismic Design Categories B and C with an importance factor of 1.0
- All plumbing components in Seismic Design Categories D, E, and F with an importance factor of 1.0 and either:
  1. Flexible connections between the components and associated elements, or
  2. Components mounted less than 4 feet (1.2 m) above floor level and weighing less than 400 pounds (181.4 kg)
- All plumbing components (suspended) in Seismic Design Categories D, E, and F with an importance factor of 1.0 and either:
  1. Flexible connections between the components and associated elements, or
  2. Components weighing 20 pounds (9.1 kg) or less or, for distribution systems, weighing 5 pounds per foot (7.4 kg/m) or less

Fixed Suspended Equipment

The most common element in this group is the suspended tank. Seldom are these heavy elements laterally braced. The best solution is to install the tank tightly against the structural member above, thus eliminating the need for bracing. However, even these tanks should be secured to the suspension system to prevent slipping. Where the element is suspended below the supporting member, cross-bracing should be installed in all directions to provide lateral stability. Where a tank is suspended near a structural wall, struts to the wall may prove to be simpler and more effective than diagonal bracing. Due to the fact that these pieces of equipment are often above ceilings or in other overhead locations, this becomes a life-safety issue.

Vibration-Isolated Floor-Mounted Equipment

This group includes units containing internal moving parts, such as pumps, motors, compressors, and engines. The codes only address damping and isolation to buildings. Manufacturers have provided seismically braced attachments to address vibrations, isolations, and damping. The effect of these attachments becomes extremely crucial in transferring noise and seismic forces. Although these devices reduce the impact of the forces to the structure, the full forces calculated are used in evaluating the attachments, beams, and structural members.

The entire concept of vibratory isolation by flotation on a non-transmitting material (spring, neoprene, cork, etc.), although necessary for equipment-operating movement, is at cross-purposes with seismic anchorage. The isolation material generally has poor lateral force-carrying capacity in itself, and the housing devices are prone to overturning. Therefore, it is necessary to either supplement conventional isolators with separate snubbing devices or install specially designed isolators that have built-in restraints and overturning resistance.

Isolators with minimal lateral force resistance used in exterior applications to resist wind are usually inadequate for large seismic forces and also commonly are made of brittle cast iron. The possibility of complete isolator unloading and the ensuing tension forces due to overturning or vertical acceleration must be considered. Manufacturers' ratings of lateral loads for isolators should be examined carefully, because often the capacity is limited by the anchorage of the isolators themselves, which typically is unspecified.

The containment surfaces in these devices must be hard connections to the piece of equipment or its base to avoid vibratory short-circuits. Because this requirement for complete operational clearance allows a small, ¼-inch (6.3-mm) movement before restraint begins, resilient pads are added to ease the shock load that could be caused by impact.

Because of the stored energy in isolation springs, it is more efficient to anchor the assembly, as restraint is built into the isolator rather than being a separate unit. In retrofit applications or occasionally due to dimensional limitations, separate snubbers are preferable. Snubbers that restrain in three dimensions are preferred because that feature minimizes the number required. Although some rubber-in-shear isolators are intended to resist loads in several directions, little data indicates their adequacy to resist the concurrent large-amplitude dynamic loading that could occur in an earthquake. Unless such isolators are considered for real earthquake loading (as opposed to code requirements) with a suitable safety factor, additional snubbing is recommended. Rubber-in-shear isolators with metal housing are more likely to have the overload capacity that may be needed to resist seismic loading, but unless they are specifically tested and rated for this loading, ultimate capacities should be compared with expected real seismic loads.

Vibration-Isolated Suspended Equipment

This is by far the most difficult type of equipment to restrain, particularly if only a small movement can be tolerated. The best method is to place an independent, laterally stable frame around the equipment with proper operating gaps padded with resilient material, similar to a snubber. However, this frame and its support system can be elaborate and awkward. An alternate method is to provide a self-contained, laterally stable, suspended platform upon which conventional seismic isolators or snubbers can be mounted.

Smaller equipment bolted or welded directly to the structure doesn't need restraints, but the bolts or welds must be designed for seismic loads. However, equipment suspended close to the structure does require restraints. Isolators within hangers always should be installed tight against the supporting structural member. When hanger rods are used to lower the unit, cross-bracing or diagonal bracing should be installed.

Cable that is installed taut, but allowed to sag under its own weight, allows vibration isolation to function. Additional slack is not required and should not be allowed. The use of neoprene grommets or bushings is not required. The cable sag and flexibility provide adequate cushioning.

SEISMIC PROTECTION TECHNIQUES FOR PIPING SYSTEMS

Typically, piping suspended by hangers less than 12 inches (305 mm) in length, as measured from the top of the pipe to the bottom of the support where the hanger is attached, does not require bracing (ASCE/SEI 7-10 Section 13.6.8, Exception 1). Seismic calculations are not required when high-deformability piping is used having provisions to avoid impact with its surroundings and meeting one of the following requirements:

- Seismic Design Categories D, E, and F, with an importance factor greater than 1.0 and pipe size equal to or less than 1 inch (25.4 mm)
- Seismic Design Category C, with an importance factor greater than 1.0 and pipe size equal to or less than 2 inches (50.8 mm)
- Seismic Design Categories D, E, and F, with an importance factor of 1.0 and pipe size less than 3 inches

(Refer to NFPA 13: *Standard for the Installation of Sprinkler Systems* for sprinkler pipe bracing.)

The following piping also shall be braced:

- Fuel oil, gas, medical gas, and compressed air piping of 1-inch (25.4-mm) nominal diameter and larger
- Piping in boiler rooms, mechanical rooms, and refrigeration mechanical rooms of 1¼-inch (31.75-mm) nominal diameter and larger

Conventionally installed piping systems have survived earthquakes with minimal damage. Fitting failures generally occur at or near equipment connectors where equipment is allowed to move or where a main is forced to move and small branches connected to the main are clamped to the structural elements. In theory, a few well-placed pipe restraints in the problem areas could provide adequate seismic protection. In practice, however, the exact configuration of piping is seldom known to the designer, and even if it was, the key brace locations are not easy to determine. Often, partial restraint in the wrong location is worse than no restraint at all. The correct practice is to provide complete restraint when seismic protection of piping systems is advisable. This restraint can be applied throughout the system or in local, well-defined areas such as mechanical or service rooms.

Although many variables must be considered when restraining pipe against seismic movement, the techniques to do so are simple and similar to those used for hanging equipment. Fixing pipe directly to structural slabs, beams, columns, or walls is the simplest method. Note that the seismic forces are considered the same in both directions. Therefore, the bracing calculated must be considered and detailed in both directions. Many codes and guidelines consider hangers of less than 12 inches (304.8 mm) as being equivalent to direct attachment. For pipes suspended more than 12 inches (304.8 mm), diagonal braces to the structure above or horizontal struts to an adjacent structure commonly are installed at vertical hanger locations. Vertical suspension hardware usually is incorporated into braces, both for efficiency and because it is readily available.

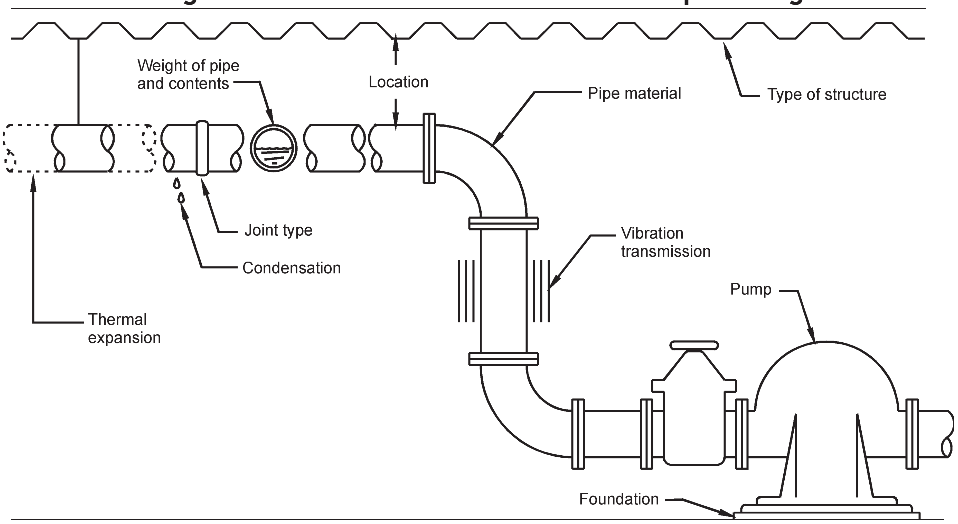
Connection to the pipe at transverse braces is accomplished by bearing the pipe or insulation on the pipe clamp or hanger. Attachment to the pipe at longitudinal brace points is not as simple. For small loads, tight-fitting clamps (such as riser clamps) dependent on friction often are used. For larger loadings, details commonly used for anchor points in high-temperature systems with welded or brazed direct connections to the piping may be necessary. Welding should be done by certified welders in accordance with AWS D1.1: *Structural Welding Code—Steel* and shall use either the shielded or submerged arc method.

Transverse bracing shall be based on the structural engineering calculations. However, certain minimum bracings must be established. Traverse bracing shall be spaced a maximum of 40 feet (12.2 m), except that fuel oil and gas piping shall be at 20-foot (6.1-m) maximum spacing. Longitudinal bracing shall be at 80-foot (24.4-m) maximum spacing, except that fuel oil and gas piping shall be at 40-foot (12.2-m) maximum spacing.

Pipe Layout Parameters

The many parameters that must be considered before the exact details and layout of a pipe bracing system can be completed are shown schematically in Figure 1. These parameters are discussed in more detail below.

Figure 1 Parameters to Be Considered for Pipe Bracing



Weight of Pipe and Contents

Since the motion being restrained is a dynamic response, the forces that must be resisted in each brace are proportional to the tributary weight.

Location of Pipe

The strength of structural members, particularly compression members, is sensitive to length, so a pipe that must run far from a structural support may require more or longer braces. In boiler service rooms, a horizontal grid of structural beams sometimes is placed at an intermediate height to facilitate the bracing of pipes. The relative position of the equipment or pipes with respect to the floor is critical.

Type of Structure

The types of structures are subdivided into the following framing categories that act as seismic force-resisting systems:

- Bearing wall systems
- Building frame systems
- Moment-resisting frame systems
- Dual systems with special moment frames capable of resisting at least 25 percent of prescribed seismic forces
- Dual systems with intermediate moment frames capable of resisting at least 25 percent of prescribed seismic forces
- Shear wall-frame interactive systems with ordinary reinforced-concrete moment frames and ordinary reinforced-concrete shear walls
- Cantilevered column systems detailed to conform to the requirements
- Steel systems not specifically detailed for seismic resistance, excluding cantilever column systems

The connection of hangers and braces to the different types of structures is an important factor in determining a bracing system. For instance, many light roof-deck systems cannot accept point loads except at beam locations; pipe locations and brace layout are thereby severely limited unless costly cross beams are placed at every brace. Other roof and floor systems have significant limitations on the magnitude of point loads, which limits brace spacing.

It is often unacceptable to drill or shoot anchors into the underneath of pre-stressed concrete floors. Limitations on depth and location also exist in the bottom flange of steel or reinforced concrete beams and in the bottom chord of joists. Many steel floor-deck styles have down flutes of 1½ inch (38.1 mm) or less in width, and the strength of drilled or shot-in anchors installed in these locations is questionable.

In buildings with structures that employ interstitial space, the capacity to brace pipe to either the top or the bottom of the space may be available, which greatly increases bracing layout flexibility.

Piping Material

The strength and ductility of the material affect brace spacing. The stiffness affects dynamic response and therefore loading. Flexible piping reduces the transmission of the forces into the building.

Joint Type

The joint has proven to be the piping system element most likely to be damaged during earthquakes. Threaded and bell-and-spigot joints are particularly susceptible. The joint type also determines, in conjunction with the pipe material, the length of the span between braces. Brazed and soldered joints perform acceptably. Most no-hub joints, however, have virtually no stiffness; thus, effective bracing of such systems is nearly impossible. Mechanical joints exhibit the most complex behavior, with spring-like flexibility (when pressurized) within a certain rotation and then rigidity. In addition, the behavior of such systems under earthquake conditions, which cause the axial loadings necessary to transmit forces to longitudinal braces, is unknown.

At a minimum, cast iron, glass pipe, and any other pipe joined with a shield-and-clamp assembly where the top of the pipe exceeds 12 inches (304.8 mm) from the supporting structure shall be braced on each side of a change in direction of 90 degrees or more. Riser joints shall be braced or stabilized between floors. For hubless pipe-riser joints unsupported between floors, additional bracing is required. All vertical pipe risers shall be laterally supported with a riser clamp at each floor.

In most engineered buildings where seismic concerns are greatly emphasized, all pipe connections near the building frame system are flexible piping.

Vibration

Traditionally, unbraced pipe systems seldom cause vibration transmission problems because of their inherent flexibility. Many engineers are concerned that completely braced, tight piping systems could cause unpredictable sound and vibration problems. Vibration isolation assists in reducing the seismic loading; however, it does not decrease the design loading of the attachments.

Temperature Movement

Pipe anchors and guides used in high-temperature piping systems must be considered and integrated into a seismic bracing system. A misplaced longitudinal brace can become an unwanted anchor and cause severe damage. Thermal forces at anchor points, unless released after the system is operational, are additive to tributary seismic forces. Potential interference between seismic and thermal support systems is particularly high near pipe bends where a transverse brace can become an anchor for the perpendicular pipe run.

Condensation

The need to thermally insulate high-temperature and chilled water lines from hanging hardware makes longitudinal brace attachment difficult. In some configurations of short runs with bends, transverse braces can be utilized near elbows to brace the system in both directions. Friction connections, using wax-impregnated oak or calcium-silicate sleeves as insulators, have been used.

Piping Bracing Methods

Several bracing systems have been developed that contain some realistic and safe details governing a wide range of loading conditions and configurations. For example, SMACNA (Sheet Metal and Air-Conditioning Contractors' National Association) has prepared some guidelines on bracing systems for use by engineers, architects, contractors, and approving authorities. These guidelines utilize three pipe-bracing methods: structural angle, structural channel, and aircraft cable. In addition, several manufacturers have developed their own seismic bracing methods. Whatever method is used, the adequacy of the supporting structure should be determined by properly applying acceptable engineering procedures.

Pipe risers seldom pose a problem because they typically are clamped at each floor, and movement due to temperature changes is routinely considered. Very large or stiff configurations, which could be affected by inter-story drift, or situations where long, free-hanging horizontal runs could be inadvertently braced by a riser are possible exceptions. The effect of mid-span couplings with less strength or rigidity than the pipe itself also must be considered.

The techniques for handling the possible differential movement at locations of utility entrances to buildings or at building expansion joints are well developed because of the similarity to the non-seismic problems of settlement, temperature movement, and wind drift. Expansion loops or combinations of mechanically flexible joints commonly are employed. For threaded piping, flexibility may be provided by the installation of swing joints. For manufactured ball joints, the length of the piping offset should be calculated using a seismic drift of 0.015 foot per foot of height above the base where seismic separation occurs. The primary consideration in seismic applications is to recognize the possibility of repeated, large differential movements.

CODE REQUIREMENTS

The process of seismic design for buildings has had a reasonably long time to mature. Beginning in the 1920s, after engineers observed heavy building damage from earthquakes, they began to consider lateral forces on buildings in this country and Japan. Today's procedures are based on analytical results as well as considerable design experience and observed performance in earthquakes of varying characteristics. Accelerations calculated for the seismic design forces are based on maximum considered earthquakes as the foundation for the most severe earthquakes considered by the codes. The lateral forces for buildings specified in most codes are much lower than could be calculated from structural dynamics for a variety of reasons, including:

- Observed acceptable performance at low design levels
- Expected ductile action of building systems (ability to continue withstanding force and distortion after yielding)
- Redundancy of resisting elements in most systems
- High damping as distortions increase, which creates a self-limiting characteristic on response
- Less-than-perfect compliance of the foundation to the ground motion
- Economic restraints on building codes

The fact that the actual response of a building during an earthquake could be three or four times that represented by code forces must be understood and considered in good seismic design. Traditionally, this was done by rule of thumb and good judgment to ensure that structural yielding is not sudden or does not produce a collapsed mechanism. More recently, the response of many distinguished buildings to real earthquake input with site-specific data is being considered more specifically than using computer analysis.

Design of seismic protection for nonstructural elements, including plumbing components and equipment, has neither the tradition nor a large number of in-place tests by actual earthquakes to enable much refinement of design force capability or design technique. Unfortunately, few of the effects listed above that mitigate the low force level for structures apply to plumbing or piping. Equipment and piping systems are generally simple and have low damping, and their lateral force-resisting systems are usually non-redundant. It is imperative, therefore, when designing seismic protection for these elements to recognize whether the force levels being utilized are arbitrarily low for design or realistic predictions of actual response. Even when predictions of actual response are used, earthquake forces are considered sufficiently unpredictable when friction is not allowed as a means of anchorage. Often, less-than-full dead load is used to both simulate vertical accelerations and provide a further safety factor against overturning or swinging action.

All current building codes require most structures and portions of structures to be designed for a horizontal force based on a certain percentage of their weight. Each code may vary in the method of determining this percentage, based on factors including the seismic zone, importance of the structure, and type of construction.

It is difficult to consider specific code requirements out of context. The code documents themselves should be consulted for specific usage. Most codes currently in use, or being developed, can be discussed generally by considering the following:

- International Building Code
- California Building Standards Code (California Code of Regulations, Title 24)
- ASCE/SEI 7
- *Seismic Design for Buildings,* U.S. Department of Defense
- *Tentative Provisions for the Development of Seismic Regulations for Buildings,* Applied Technology Council

The Lateral Force

All of these codes require consideration of a lateral force that must be placed at the center of gravity of the element. The lateral force, or equivalent static force, is calculated using some or all of the following parameters.

Zone

The zone category affects the lateral force calculated by considering the size and frequency of potential earthquakes in the region. Zones vary from no earthquakes (Zone 0) to a majority of California (Zone 4).

Soil

The effect of specific site soils on ground motion must be considered. Soil types are divided based on three characteristics: soil shear wave velocity, standard penetration resistance, and soil undrained shear strength. The types of soils are:

A: Hard rock
B: Rock
C: Very dense soil and soft rock
D: Stiff soil profile
E: Soft soil profile or near liquefaction
F: Full liquefaction

Site Coefficient

The site coefficient considers the basic response of the element to ground motion and is affected by sub-parameters, which could include location within the building and possible resonance with the structure. Given the exact latitude and longitude of the location, U.S. Geological Survey data can provide all of the parameters based on exact location with respect to all fault lines occurring within the vicinity. All parameters are site specific, and the data provided includes a site coefficient based on the maximum considered earthquake for short (less than 0.04 second) and long (less than 1 second) periods, as well as the accelerations for corresponding periods.

Importance Factor

The importance factor is a measure of the desirability of protection for a specific element. The importance factor ranges from 1.0 for ordinary buildings to 1.5 for hospitals and police stations.

Element Weight

All codes require calculation of a lateral force that is a percentage of the element weight. The tributary weight that the lateral forces encounter is the whole or partial weight of the equipment or element depending on its position within the building.

Amplification Factor

The amplification factor is defined by the natural period, damping ratio, and mass of the equipment and the structure. This amplifies certain critical connections and allows a higher level of bonding of the equipment and the building.

Response Factor

Determined by driven frequency (equipment motors) and natural frequency, the response factor depends on the rigidity and flexibility of the connection. This becomes critical in the case of non-building structures such as tanks, billboards, and other equipment that are totally self-supporting. When the fundamental period of the structure, T, is less than 0.06 second, then the structure is considered rigid. The response factor increases as the connection becomes more flexible.

Sprinkler Systems: NFPA 13

Because of the potential for fire immediately after earthquakes, sprinkler piping has long received special attention. The reference standard for the installation of sprinkler piping, NFPA 13, often is cited as containing prototype seismic bracing for piping systems. In fact, in those cases observed, sprinkler piping has performed well. In addition to bracing, good earthquake performance by sprinkler piping is also due to other factors, such as limited pipe size, the use of steel pipe, coherent layouts, and conservative suspension (for vertical loads).

Use of NFPA 13 guidelines for pipe bracing is not discouraged, but it should not be considered a panacea for all piping systems. Other organizations, such as FM Global, have developed guidelines for properties insured by them and in many cases are more restrictive.

For reference, Table 1 provides the weights of steel pipe filled with water for determining horizontal loads, Table 2 provides load information for the spacing of sway bracing, and Table 3 provides maximum horizontal loads for sway bracing.

Table 1 Piping Weights for Determining Horizontal Load

Schedule 40 Pipe, in. (mm)	Weight of Water-Filled Pipe, lb/ft (kg/m)	One-Half Weight of Water-Filled Pipe, lb/ft (kg/m)
1 (25.4)	2.05 (0.28)	1.03 (0.14)
1¼ (31.8)	2.93 (0.40)	1.47 (0.20)
1½[a] (38.1)	3.61 (0.50)	1.81 (0.25)
2 (50.8)	5.13 (0.70)	2.57 (0.35)
2½ (63.5)	7.89 (1.08)	3.95 (0.54)
3 (76.2)	10.82 (1.48)	5.41 (0.74)
3½ (88.9)	13.48 (1.85)	6.74 (0.92)
4 (101.6)	16.40 (2.25)	8.20 (1.12)
5 (127)	23.47 (3.22)	11.74 (1.61)
6 (152.4)	31.69 (4.35)	15.85 (2.17)
8[b] (203.2)	47.70 (6.54)	23.85 (3.27)
Schedule 10 Pipe, in. (mm)	**Weight of Water-Filled Pipe, lb/ft (kg/m)**	**One-Half Weight of Water-Filled Pipe, lb/ft (kg/m)**
1 (25.4)	1.81 (0.25)	0.91 (0.12)
1¼ (31.8)	2.52 (0.35)	1.26 (0.17)
1½ (38.1)	3.04 (0.42)	1.52 (0.21)
2[a] (50.8)	4.22 (0.58)	2.11 (0.29)
2½ (63.5)	5.89 (0.81)	2.95 (0.40)
3 (76.2)	7.94 (1.09)	3.97 (0.54)
3½ (88.9)	9.78 (1.34)	4.89 (0.67)
4 (101.6)	11.78 (1.62)	5.89 (0.81)
5 (127)	17.30 (2.37)	8.65 (1.19)
6 (152.4)	23.03 (3.16)	11.52 (1.58)
8 (203.2)	40.08 (5.50)	20.04 (2.75)

a Maximum pipe size within 12″ of the roof framing that does not require seismic bracing calculations
b Schedule 30

Table 2 Assigned Load Table for Lateral and Longitudinal Sway Bracing[a]

Spacing of Lateral Braces, ft (m)	Spacing of Longitudinal Braces, ft (m)	Assigned Load for Pipe Size to Be Braced, lb (kg)						
		2	2½	3	4	5	6	9
10 (3.0)	20 (6.0)	380 (171.0)	395 (177.8)	410 (184.5)	435 (195.8)	470 (211.5)	655 (294.8)	915 (411.8)
20 (6.0)	40 (12.2)	760 (342.0)	785 (353.3)	815 (366.8)	870 (391.5)	940 (423.0)	1,305 (587.3)	1,830 (823.5)
25 (7.6)	50 (15.2)	950 (427.5)	980 (441.0)	1,020 (459.0)	1,090 (490.5)	1,175 (528.8)	1,630 (733.5)	2,290 (1030.5)
30 (9.1)	60 (18.3)	1,140 (513.0)	1,180 (531.0)	1,225 (551.3)	1,305 (587.3)	1,410 (634.5)	1,960 (882.0)	2,745 (1235.3)
40 (12.2)	80 (24.4)	1,515 (681.8)	1,570 (706.5)	1,630 (733.5)	1,740 (783.0)	1,880 846.0)	2,610 (1174.5)	3,660 (1647.0)
50 (15.2)		1,895 (852.8)	1,965 (884.3)	2,035 (915.8)	2,175 (978.8)	2,350 (1057.5)	3,260 (1467.0)	4,575 (2058.8)

Note: Table is based on half the weight of a water-filled pipe.
a Minimum required bracing. All connections for these pipes must be verified with full Professional Engineer's structural engineering calculations.

ANALYSIS TECHNIQUES

Determination of Seismic Forces

As discussed in the previous section, one of the most common methods of defining seismic forces is by use of code equivalents of dynamic earthquake forces. The following formula can be used to determine the loading.

Equation 9-1

$$F_p = 0.4\ a_p S_{DS} W_p (1 + 2\ z/h)/(R_p/I_p)$$

where:

F_p = Lateral (seismic) force applied at element center of gravity (Must be within the maximum value of $1.6 S_{DS} W_p I_p$ and the minimum value of $0.30 S_{DS} W_p I_p$.)

S_{DS} = Coefficient considering the parameters discussed above. The final percentage of the element weight often is described in units of g, the acceleration of gravity (e.g., 0.5 g). This is equivalent to specifying a percentage of the weight; thus, 0.5 = 50 percent of W.

W_p = Weight tributary to anchorage (pipe and contents)

I_p = Importance factor, ranging from 1.0 to 1.5 (Section 13.1.3 of ASCE 7-10)

h = Height of the building roof from ground level

z = Vertical distance from ground level to equipment location. Height in structure of point of anchorage of the component with respect to the base. Where components at or below the ground level, z shall be taken as 0. The value of z/h cannot exceed 1.0.

R_p = Component response modification factor, varying from 1 to 12 (Select appropriate value from Table 13.5-1 or 13.6-1 of ASCE 7-10)

a_p = Component amplification factor that varies from 1 to 2.5 (select appropriate value from Table 13.5-1 or 13.6-1)

Since F_p is a representation of vibratory response, it can be applied in a plus or minus sense.

In piping systems, since vertical supports are placed more frequently than lateral braces, W_p is greater than the dead load supported at that point. This mismatching of F_p and available dead load often causes uplift on the pipe, which should be taken into consideration.

The loading (F_p) also can be calculated using a response spectrum determined for the appropriate floor or by modeling the equipment or piping as part of the structure and, by computer, inputting an appropriate time history of motion at the base. In practice, these techniques are seldom used, except in buildings of extreme importance or when the mass of the equipment becomes a significant percentage of the total building mass. (10 percent is sometimes used as the limit.) Where the weight of a nonstructural component is greater than or equal to 25 percent of the effective seismic weight, W, it shall be designed for a non-building structure in accordance with Section 15.3.2 of ASCE 7-10. The effective seismic weight is the dead load as defined in Section 3.1 of ASCE 7-10.

For non-building structures such as independent cooling towers, tanks, etc., the following formula can be used for weights of non-building structures greater than or equal to 25 percent of the combined effective seismic weights.

Equation 9-2

$$F_p = 0.8 S_1 W_p/(R/I)$$

where:

F_p = Lateral (seismic) force applied at element center of gravity (Cannot be less than 0.03 W_p.)

S_1 = Spectral response acceleration, at mapped maximum considered earthquake at 1 second with 5 percent damped

R = Response modification coefficient as noted in tabulation

I = Importance factor

W_p = Weight tributary

Table 3 Maximum Horizontal Loads for Sway Bracing[a]

Shape and Size, in. (mm)		Least Radius of Gyration	Maximum Length for 1/r = 200	Maximum Horizontal Load, lb (kg) 30-44° Angle from Vertical	45-59° Angle from Vertical	60-90° Angle from Vertical
Pipe (Schedule 40)				$= (\sqrt{r_0^2 + r_1^2})/2$		
1	(25.4)	0.42	7 ft 0 in (2.1 m)	1,767 (801.5)	2,500 (1,134.0)	3,061 (1,388.4)
1¼	(31.8)	0.54	9 ft 0 in (2.7 m)	2,393 (1,085.4)	3,385 (1,535.4)	4,145 (1,880.1)
1½	(38.1)	0.623	10 ft 4 in (3.1 m)	2,858 (1,296.4)	4,043 (1,833.9)	4,955 (2,241.5)
2	(50.8)	0.787	13 ft 1 in (4.0 m)	3,828 (1,736.3)	5,414 (2,455.7)	6,630 (3,007.3)
Pipe (Schedule 10)				$= (\sqrt{r_0^2 + r_1^2})/2$		
1	(25.4)	0.43	7 ft 2 in (2.2 m)	1,477 (670.0)	2,090 (948.0)	2,559 (1,160.7)
1¼	(31.8)	0.55	9 ft 2 in (2.8 m)	1,900 (861.8)	2,687 (1,218.8)	3,291 (1,492.8)
1½	(38.1)	0.634	10 ft 7 in (3.2 m)	2,194 (995.2)	3,103 (1,407.5)	3,800 (1,723.6)
2	(50.8)	0.802	13 ft 4 in (4.1 m)	2,771 (1,256.9)	3,926 (1,780.8)	4,803 (2,178.6)
Angles						
1½ x 1½ x ¼	(38.1 x 38.1 x 6.4)	0.292	4 ft 10 in (1.5 m)	2,461 (1,116.3)	3,481 (1,578.9)	4,263 (1,933.7)
2 x 2 x ¼	(50.8 x 50.8 x 6.4)	0.391	6 ft 6 in (2 m)	3,356 (1,522.2)	4,746 (2,152.7)	5,813 (2,636.7)
2½ x 2 x ¼	(63.5 x 50.8 x 6.4)	0.424	7 ft 0 in (2.1 m)	3,792 (1,720.0)	5,363 (2,432.6)	6,569 (2,979.6)
2½ x 2½ x ¼	(63.5 x 63.5 x 6.4)	0.491	8 ft 2 in (2.5 m)	4,257 (1,930.9)	6,021 (2,731.1)	7,374 (3,344.8)
3 x 2½ x ¼	(76.2 x 63.5 x 6.4)	0.528	8 ft 10 in (2.7 m)	4,687 (2,126.0)	6,628 (3,006.4)	8,118 (3,682.2)
3 x 3 x ¼	(76.2 x 76.2 x 6.4)	0.592	9 ft 10 in (3 m)	5,152 (2,336.9)	7,286 (3,304.9)	8,923 (4,047.4)
Rods				$= r/2$		
⅜	(9.5)	0.094	1 ft 6 in (0.5 m)	395 (179.2)	559 (253.6)	685 (310.7)
½	(12.7)	0.125	2 ft 6 in (0.8 m)	702 (318.4)	993 (450.4)	1,217 (552.0)
⅝	(15.9)	0.156	2 ft 7 in (0.8 m)	1,087 (493.1)	1,537 (697.2)	1,883 (854.1)
¾	(19.1)	0.188	3 ft 1 in (0.9 m)	1,580 (716.7)	2,235 (1,013.8)	2,737 (1,241.5)
⅞	(22.2)	0.219	3 ft 7 in (1.1 m)	2,151 (975.7)	3,043 (1,380.3)	3,726 (1,690.1)
Flats				$= 0.29\ h$ (where h is smaller of two side dimensions)		
1½ x ¼	(38.1 x 6.4)	0.0725	1 ft 2 in (0.4 m)	1,118 (507.1)	1,581 (717.1)	1,936 (878.2)
2 x ¼	(50.8 x 6.4)	0.0725	1 ft 2 in (0.4 m)	1,789 (811.5)	2,530 (1,147.6)	3,098 (1,405.2)
2 x ⅜	(50.8 x 9.5)	0.109	1 ft 9 in (0.5 m)	2,683 (1,217.0)	3,795 (1,721.4)	4,648 (2,108.3)
Pipe (Schedule 40)				$= (\sqrt{r_0^2 + r_1^2})/2$		
1	(25.4)	0.42	3 ft 6 in (1.1 m)	7,068 (3,206.0)	9,996 (4,534.1)	12,242 (5,552.8)
1¼	(31.8)	0.54	4 ft 6 in (1.4 m)	9,567 (4,339.5)	13,530 (6,137.1)	16,570 (7,516.0)
1½	(38.1)	0.623	5 ft 2 in (1.6 m)	11,441 (5,189.5)	16,181 (7,339.5)	19,817 (8,988.8)
2	(50.8)	0.787	6 ft 6 in (2 m)	15,377 (6,974.9)	21,746 (9,863.8)	26,634 (12,080.9)
Pipe (Schedule 10)				$= (\sqrt{r_0^2 + r_1^2})/2$		
1	(25.4)	0.43	3 ft 7 in (1.1 m)	5,910 (2,680.7)	8,359 (3,791.6)	10,237 (4,643.4)
1¼	(31.8)	0.55	4 ft 7 in (1.4 m)	7,600 (3,447.3)	10,749 (4,875.6)	13,164 (5,971.1)
1½	(38.1)	0.634	5 ft 3 in (1.6 m)	8,777 (3,981.2)	12,412 (5,630.0)	15,202 (6,895.5)
2	(50.8)	0.802	6 ft 8 in (2 m)	11,105 (5,037.1)	15,705 (7,123.6)	19,235 (8,724.8)
Rods				$= r/2$		
⅜	(9.5)	0.094	0 ft 9 in (0.2 m)	1,580 (716.7)	2,234 (1,013.3)	2,737 (1,241.5)
½	(12.7)	0.125	1 ft 0 in (0.3 m)	2,809 (1,274.1)	3,972 (1,801.7)	4,865 (2,206.7)
⅝	(15.9)	0.156	1 ft 3 in (0.4 m)	4,390 (1,991.3)	6,209 (2,816.3)	7,605 (3,449.6)
¾	(19.1)	0.188	1 ft 6 in (0.5 m)	6,322 (2,867.6)	8,941 (4,055.5)	10,951 (4,967.3)
⅞	(22.2)	0.219	1 ft 9 in (0.5 m)	8,675 (3,934.9)	12,169 (5,519.7)	14,904 (6,760.3)
Pipe (Schedule 40)				$= (\sqrt{r_0^2 + r_1^2})/2 \quad 1/r = 300$		
1	(25.4)	0.42	10 ft 6 in (3.2 m)	786 (356.5)	1,111 (503.9)	1,360 (616.9)
1¼	(31.8)	0.54	13 ft 6 in (4.1 m)	1,063 (482.2)	1,503 (681.7)	1,841 (835.1)
1½	(38.1)	0.623	15 ft 7 in (4.7 m)	1,272 (577.0)	1,798 (815.5)	2,202 (998.8)
2	(50.8)	0.787	19 ft 8 in (6 m)	1,666 (755.7)	2,355 (1,068.2)	2,885 (1,308.6)
Pipe (Schedule 10)				$= (\sqrt{r_0^2 + r_1^2})/2$		
1	(25.4)	0.43	10 ft 9 in (3.3 m)	656 (297.8)	928 (420.9)	1,137 (515.7)
1¼	(31.8)	0.55	13 ft 9 in (4.2 m)	844 (383.2)	1,194 (541.6)	1,463 (663.6)
1½	(38.1)	0.634	15 ft 10 in (4.8 m)	975 (442.3)	1,379 (625.5)	1,194 (541.6)
2	(50.8)	0.802	20 ft 0 in (6.1 m)	1,234 (559.7)	1,745 (791.5)	2,137 (969.3)
Rods				$= r/2$		
⅜	(9.5)	0.094	2 ft 4 in (0.7 m)	176 (79.8)	248 (112.5)	304 (137.9)
½	(12.7)	0.125	3 ft 1 in (0.9 m)	312 (141.5)	441 (200.0)	540 (244.9)
⅝	(15.9)	0.156	3 ft 11 in (1.2 m)	488 (221.4)	690 (313.0)	845 (383.3)
¾	(19.1)	0.188	4 ft 8 in (1.4 m)	702 (318.4)	993 (450.4)	1,217 (552.0)
⅞	(22.2)	0.219	5 ft 6 in (1.7 m)	956 (433.6)	1,352 (613.3)	1,656 (751.1)

a Minimum required bracing. All connections for these pipes must be verified with full Professional Engineer's structural engineering calculations.

Determination of Anchorage Forces

In most cases, anchorage or reaction forces, R_h and R_v, created by the loading described above, are calculated by simple moment diagrams. Although trivial for a professional familiar with statistics, calculations to find all maximums become numerous when the center of gravity is off one or both plan centerline axes or if the base support is non-symmetrical.

In typical pipe braces, it is important to note that R, the gravity force in the hanger rod, is affected significantly by the addition of the brace and is not equal to W, as indicated previously. Dealing with these loads is a huge problem. A tension rod hanger commonly goes into compression in such a situation. Cable restraints do not have this problem.

COMPUTER ANALYSIS OF PIPING SYSTEMS

Computer programs have been used to analyze piping systems for stress for some time. These programs initially were developed to consider thermal stresses and anchor point load, but software now can consider seismic and settlement loading, spring or damping supports, snubbers (similar to equipment snubbers), differing materials, and non-rigid couplings. The seismic loading can be determined by using a full-time history, as a response spectrum, or equivalent static forces. The time history has the inherent problem of requiring a search of each time increment for worst-case stresses and brace loadings. The computer time and man-hours required are seldom justified.

In fact, for seismic loading alone, computer analysis is almost never performed because brace loadings easily can be determined by tributary length methods, and rule-of-thumb pipe spans (brace spacing) are contained in several publications (see NFPA 13, *Seismic Restraint Manual: Guidelines for Mechanical Systems,* and *Seismic Design for Buildings*). Computer analysis may be appropriate, however, when it is necessary to combine seismic loading with several of the following considerations:

- Temperature changes and anchorage
- Nonlinear support conditions (springs, snubbers, etc.)
- Complex geometry
- Several loading conditions
- Piping materials other than steel or copper
- Joints or couplings that are significantly more flexible or weaker than the pipe itself

Because of the variety of computer programs available and because many have proprietary restrictions, specific programs are not listed here.

Loads in Structures

It is always important to identify unusual equipment and piping loads during the first stages of project design to ensure that the structural system being developed is adequate. Consideration of seismic effects makes this coordination even more important because seismic forces produce unusual reactions. During an earthquake, horizontal forces must be taken into the structure, and vertical load effects are intensified due to vertical accelerations and overturning movements. These reactions must be acceptable to the structure locally (at the point of connection) and globally (by the system as a whole).

If the structural system is properly designed for the appropriate weights of equipment and piping, seismic reactions will seldom cause problems to the overall system. However, local problems are not uncommon. Most floors are required by code to withstand a 2,000-pound concentrated load, so this is a reasonable load to consider acceptable without special provisions. However, seismic reactions to structures can easily exceed this figure. For example:

- A longitudinal brace carrying a tributary load of 80 feet of 8-inch steel pipe filled with water generates reactions of this magnitude.
- Transverse or longitudinal braces on trapezes often have larger reactions.
- A 4,000-pound tank on legs also could yield such a concentrated load.

In addition, possible limitations on attachment methods due to structure type could reduce the effective maximum allowable concentration.

Roof structures have no code-specified concentrated load requirement and often are the source of problems, particularly concerning piping systems, because of the random nature of hanger and brace locations. Many roof-decking systems cannot accept concentrations greater than 50 pounds without spreaders or strengthening beams. Such limitations should be considered in both the selection of a structural system and the equipment and piping layout.

If equipment anchorage or pipe bracing is specified to be contractor supplied, attachment load limitations or other structural criteria should be given. Compliance with such criteria should be checked to ensure that the structure is not being damaged or overloaded.

POTENTIAL PROBLEMS

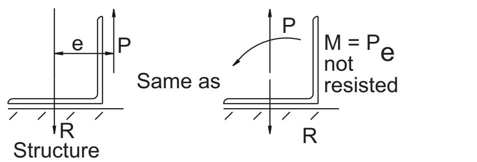
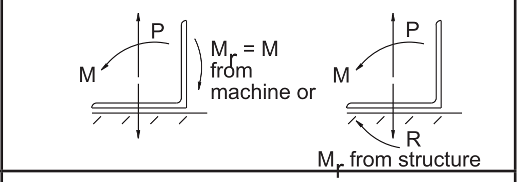
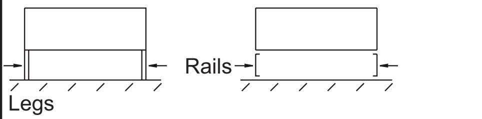
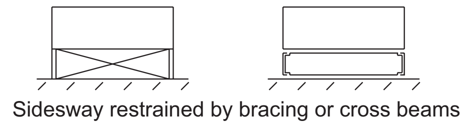
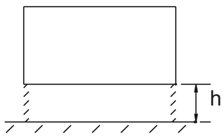
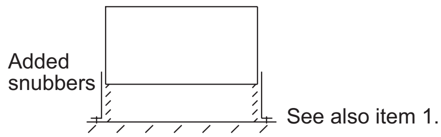
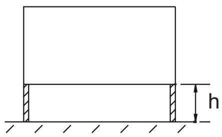
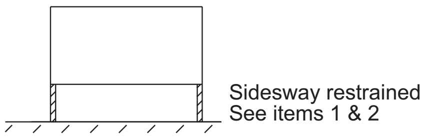
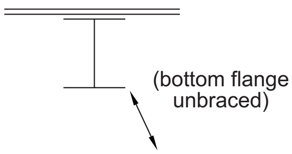
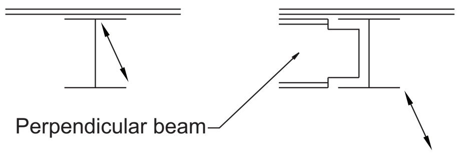
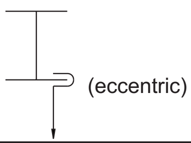
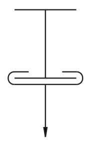
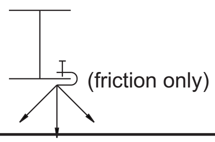
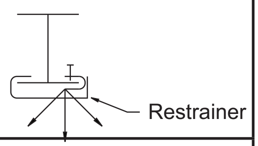
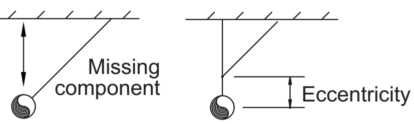
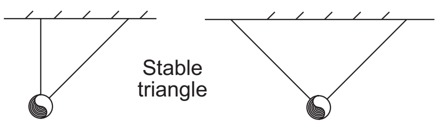
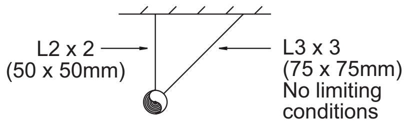
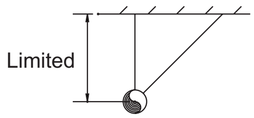
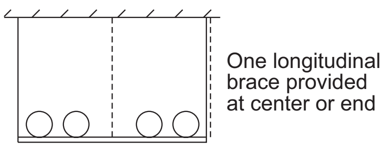
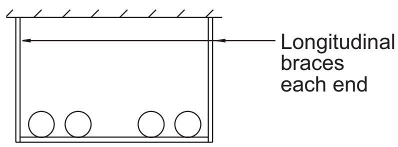
It would be impractical to cover the details of structural design for seismic anchorage and bracing in this chapter. The engineer can get design information and techniques from standard textbooks and design manuals or, preferably, obtain help from a professional experienced in seismic and/or structural design. Simple, typical details are seldom appropriate, and all-encompassing seismic protection systems quickly become complex. Certain common situations that have the potential to create problems can be identified, however. These are shown schematically in Figure 2 and discussed below.

Condition 1 in Figure 2 occurs frequently in making attachments to concrete. Often an angle is used, as indicated. The seismic force, P, enters the connector eccentric to the reaction, R, by the distance e; this is equivalent to a concentric force plus the moment P_e. For the connector to perform as designed, this moment must be resisted by the connection of the angle either to the machine or to the concrete. To use the machine to provide this moment, the machine base must be adequate, and the connection from the angle to the base must be greatly increased over that required merely for P. Taking this moment into the concrete significantly increases the tension in the anchorage, R, which is known as prying action. The appropriate solution must be decided on a case-by-case basis, but eccentricities in connections should not be ignored.

Legs 18 inches (0.5 m) or longer on supporting tanks or machines clearly create a sideways problem and commonly are cross-braced. However, shorter legs or even rails often have no strength or stiffness in their weak direction, as shown in Condition 2, and also should be restrained against base failure.

Conditions 3 and 4 point out that spring isolators typically create a significant height, h, through which lateral forces must be transmitted. This height, in turn, creates conditions similar to the problems shown in 1 and 2 and must be treated in the same manner.

Figure 2 Potential Problems in Equipment Anchorage or Pipe Bracing

Condition	Potential Problems in Design Probably Not Acceptable	Seismic Protection Probably Acceptable
1. Eccentricity in connection		
2. Sidesway or tipping		
3. Isolators with no restraint		
4. Isolators with restraint		
5. Location of connection to structure (lateral force)		
6. Location of connection to structure (vertical force)		
7. Type of connector		
8. Brace configuration		
9. "Typical" details		
10. Trapeze		

Condition 5 is meant to indicate that the bottom flange of a steel beam seldom can resist a horizontal force; diagonal braces, which often are connected to bottom flanges, create such a horizontal force. This condition can be rectified by attaching the diagonal brace near the top flange or adding a stabilizing element to the bottom flange.

Condition 6 depicts a typical beam connection device (beam clamp), which slips over one flange. Although this is often acceptable, significant stresses can be introduced into the beam if the load is large or the beam is small. Considering the variability and potential overload characteristics of seismic forces, this condition should be avoided. Condition 7 also shows a connector in common use, which is acceptable in a non-seismic environment but should be secured in place as shown under dynamic conditions.

Most pipe bracing systems utilize bracing members in pure tension or compression for stiffness and efficiency. This truss-type action is possible only when bracing configurations make up completed triangles, as shown on the right under Condition 8. The brace configuration on the far left is technically unstable, and the eccentric condition shown produces moment in the vertical support.

As previously indicated, typical details must be designed and presented carefully to prevent their misuse. Condition 9 shows the most common deficiency: a lack of limiting conditions.

Condition 10 shows a situation often seen in the field where interferences may prevent the placement of longitudinal braces at the ends of a trapeze and either one is simply left out or two are replaced by one in the middle. Both of these substitutions can cause an undesirable twist of the trapeze and subsequent pipe damage. All field revisions to bracing schemes should be checked for adequacy.

Other potential problems that occur less frequently include the incompatibility of piping systems with the differential movement of the structure and the inadvertent self-bracing of piping through short, stiff service connections or branches that penetrate the structure. If the possibility of either is apparent, pipe stresses should be checked or the self-bracing restraint should be eliminated.

A few problems associated with making a connection to a structure were discussed above, in relation to Figure 2. When connecting to structural steel, in addition to manufactured clip devices, bolting and welding are also used. Holes for bolting should never be placed in structural steel without the approval of the structural engineer responsible for the design. Field welding should consider the effects of elevated temperatures on loaded structural members.

The preferred method of connecting to concrete is through embedments, but this is seldom practical. Since the location of required anchorages or braces often is not known when concrete is poured, the use of drilled-in or shot-in anchors is prevalent for this purpose. Although these anchors are extremely useful and necessary connecting devices, their adequacy has many sensitivities, and they should be applied with thorough understanding and caution. The following items should be considered in the design or installation of drilled or shot-in anchors.

- Manufacturers often list ultimate (failure) values in their literature. Normally, factors of safety of 4 or 5 are applied to these values for design.
- Combined shear and tension should be considered in the design. A conservative approach commonly used is the following equation.

Equation 9-3

$$(T/T_a) + (V/V_a) < 1$$

where:

T = Tension, lbf/in²

T_a = Allowable tension, lbf/in²

V = Shear, lbf/in²

V_a = Allowable shear, lbf/in²

Edge distances are important because of the expansive nature of these anchors. Six diameters typically are required.

Review the embedments required for design values. Embedment is defined as full penetration of the bolt/nail with at least 8 diameters of the bolt/nail. For example, a ½-inch (12.7-mm) lag bolt will require 4 inches (101.6 mm) of full penetration of that bolt. If such distances are not available, then this is considered a shallow penetration, and the value of R, the response modification coefficient, shall be reduced. It is difficult to install an expansion bolt more than ½ inch (12.7 mm) in diameter in a typical floor system of 2½-inch (63.5-mm) concrete over steel decking.

Bolt sizes more than ¼ inch (6.35 mm) in diameter have embedments sufficient to penetrate the reinforcing envelope. Thus, bolts should not be placed in columns, the bottom flange of beams, or the bottom chord of joists. Bolts in slabs or walls are less critical, but the possibility of special and critical reinforcing bars being cut should be considered. The critical nature of each strand of tendon in pre-stressed concrete, as well as the stored energy, generally dictates a complete prohibition of these anchors.

Installation technique has been shown to be extremely important in developing design strength. Field testing of a certain percentage of anchors should be considered.

ADDITIONAL CONSIDERATIONS

Seismic anchorage and bracing, like all construction, should be thoroughly reviewed in the field. Considering the lack of construction tradition, the likelihood of field changes or interferences, and other potential problems (discussed above), seismic work should be more clearly controlled, inspected, and tested than normal construction.

Another result of the relative newness of seismic protection of equipment and piping is the lack of performance data for the design and detailing techniques now being used. Essentially no field data is available to ensure that present assumptions, although scientifically logical and accurate, will actually provide the desired protection. Will firm anchorage of equipment damage the internal workings? Will the base cabinet or framework (which is seldom checked) of equipment be severely damaged by the anchorage? The present requirements are largely the result of observations of damage to structures in actual earthquakes over 75 years.

The net result of current standards in seismic protection can only be positive. The fine-tuning of scope, force levels, and detailing techniques must wait for additional, full-scale testing in real earthquakes.

GLOSSARY

Acceleration 1. Change from one speed or velocity to another. 2. The rate at which the velocity of a body changes with time commonly measured in "g" (an acceleration of 32 ft/sec/sec or 980 cm/sec/sec = gravity constant on earth).

Accelerogram The graphical output from an accelerograph or seismograph showing acceleration as a function of time.

Accelerograph Also known as a seismograph or an accelerometer, an instrument that records ground acceleration during an earthquake.

Amplitude Deviation from mean of the centerline of a wave.

Anchor A device, such as an expansion bolt, for connecting pipe-bracing members to the structure of a building.

Attachment See *positive attachment.*

Bracing Metal channels, cables, or hanger angles that prevent pipes from breaking away from the structure during an earthquake. See also *longitudinal bracing* and *transverse bracing*. Together, these resist lateral loads from any direction.

Center of mass Also known as center of gravity, the unique point where the weighted relative position of the distributed mass sums to zero.

Creep (along a fault) Slow movement along a fault due to ongoing tectonic deformation.

Crust/lithosphere The outermost major layer of the Earth, ranging from 10 to 80 kilometers in thickness. It is made up of crustal rocks, sediment, and basalt. The general composition is silicon-aluminum-iron.

Damping The rate at which natural vibration decays as a result of the absorption of energy.

Deflection The displacement of a building element due to the application of external force.

Ductility Ability to withstand inelastic strain without fracturing.

Duration The period of time within which ground acceleration occurs.

Dynamic 1. The branch of mechanics concerned with the forces that cause motions of bodies. 2. The property of a building when it is in motion.

Dynamic properties of piping The tendency of pipes to change in weight and size because of the movement and temperature of fluids in them. This does not refer to movement due to seismic forces.

Eccentric Not having a common center; not concentric.

Epicenter The point of the Earth's surface directly above the focus or hypocenter of an earthquake.

Equipment For the purposes of this chapter, the mechanical devices associated with pipes that have significant weight. Examples include pumps, tanks, and electric motors.

Essential facilities Buildings that must remain safe and usable for emergency purposes after an earthquake to preserve the health and safety of the general public. Examples include hospitals, emergency shelters, and fire stations.

Fault A fracture or crack in the Earth's crust across which relative displacement has occurred.

Frequency 1. The number of wave peaks or cycles per second. 2. The inverse of period.

Fundamental or natural period 1. The elapsed time, in seconds, of a single cycle of oscillation. 2. The inverse of frequency.

Gas pipe For the purposes of this chapter, any pipe that carries fuel gas, fuel oil, medical gas, vacuum, or compressed air.

Hooke's law In mechanics and physics, an approximation stating that the extension of a spring is in direct proportion with the load applied to it. Mathematically, Hooke's law states that F= kx, where x is the displacement of the spring's end from its equilibrium position (meters), F is the restoring force exerted by the spring on that end (N or $kg{\cdot}m/s_2$), and k is a constant called the rate or spring constant (N/m or kg/s_2).

Hypocenter/focus The point below the epicenter at which an earthquake rupture starts.

Inelastic Non-recoverable deformation of an element.

Inertial forces The product of mass times acceleration (F = ma).

Input motion The seismic forces applied to a building or structure.

Intensity A subjective measure describing the severity of an earthquake in terms of its effects on persons, structures, and the Earth's surface, depicted as a Roman numeral based on the Modified Mercalli (MM) version ranging from MM-I (not felt) through MM-XII (nearly total damage).

Landslide Movement or land disturbance on a hillside where material slides down a slope.

Lateral force A force acting on a pipe in the horizontal plane. This force can be in any direction.

Longitudinal bracing Bracing that prevents a pipe from moving in the direction of its run.

Longitudinal force A lateral force that happens to be in the same direction as the pipe.

Magnitude A measure of the relative size of an earthquake describing the amount of energy released. See *Richter scale.*

Mass The property of a body that causes it to have weight in a gravitational field.

Natural or fundamental frequency The frequency at which a particular object or system vibrates when pushed by a single force or impulse and not influenced by other external forces or by damping.

Nonstructural components Components not intended primarily for the structural support of the building.

OSHPD Office of Statewide Health Planning and Development (California).

Oscillation Regular periodic variation in value about a mean.

Period 1. The elapsed time in seconds of a single cycle of oscillation. 2. The time interval required for one full cycle of a wave. 3. The inverse of frequency.

Plate tectonics The theory supported by a wide range of evidence that considers the Earth's crust and upper mantle to be composed of several large, thick, relatively rigid plates that move relative to one another. This theory studies plate formation, movement, interaction, and destruction.

Positive attachment A mechanical device designed to resist seismic forces that connects a nonstructural element, such as a pipe, to a structural element, such as a beam. Bolts and screws are examples of positive attachments. Glue and friction due to gravity do not create positive attachments.

Resonance A vibration of large amplitude produced by a relatively small vibration near the same frequency of vibration as the natural frequency of the resonating system.

Response spectrum Maximum response of a site plotted against increasing periods.

Richter scale Developed in 1935 by Charles F. Richter of the California Institute of Technology, a device that compares the size of earthquakes by describing the amount of energy released.

Rigidity 1. The physical property of being stiff and resisting bending. 2. The relative stiffness of a structure or element. 3. In numerical terms, equal to the reciprocal of displacement caused by a unit force.

Seiche A wave on the surface of water in an enclosed or semi-enclosed basin caused by atmospheric or seismic disturbances.

Seismic Subject to or caused by an earthquake or earth vibration. Seismic loads on a structure are caused by wave movements in the Earth during an earthquake.

Spectra A plot indicating maximum earthquake response with respect to the natural period or frequency of the structure or element. Response can show acceleration, velocity, displacement, shear, or other properties of response.

Stability 1. The strength to stand or endure. 2. Resistance to displacement or overturning.

Stiffness A measure of deflection or of staying in alignment within a certain stress.

Strength 1. Power to resist force. 2. A measure of load bearing without exceeding a certain stress.

Stress 1. The deformation caused in a body by such a force. 2. Internal resistance within a material opposing a force to deform it.

Transverse bracing Bracing that prevents a pipe from moving from side to side.

Tsunami A sea wave produced by submarine earth movement or volcanic eruption.

Velocity 1. The rate of change of position along a straight line with respect to time 2. The derivative of position with respect to time measured in centimeters/second.

Vibration 1. A periodic motion that repeats itself after a definite interval of time. 2. The periodic motion of the particles of an elastic body or medium in alternately opposite directions from the position of equilibrium when that equilibrium has been disturbed

Wave "P" 1. The primary or compressional wave. 2. The fastest waves traveling away from a seismic event through the Earth's crust, which shake the ground back and forth in the same direction and the opposite direction as the direction the wave is moving.

Wave "S" Secondary or shear wave, which shakes the ground back and forth perpendicular to the direction the wave is moving.

RESOURCES

- ASCE/SEI 7-10: *Minimum Design Loads for Buildings and Other Structures,* American Society of Civil Engineers
- ATC-3: *Tentative Provisions for the Development of Seismic Regulation for Buildings,* Applied Technology Council
- "Nonstructural damage. The San Fernando, California, Earthquake of February 9, 1971," National Oceanic and Atmospheric Administration
- "Nonstructural Damage to Buildings. The Great Alaska Earthquake of 1964: Engineering," National Academy of Sciences
- California Building Standards Code (California Code of Regulations, Title 24)
- *Guidelines for Seismic Restraints of Mechanical Systems,* Sheet Metal Industry Fund
- *Automatic Sprinkler Systems Handbook*, National Fire Protection Association
- NFPA 13: *Standard for the Installation of Sprinkler Systems*, National Fire Protection Association
- *Seismic Restraint Manual: Guidelines for Mechanical Systems*, Sheet Metal and Air Conditioning Contractors' National Association
- *Seismic Design for Buildings,* U.S. Department of Defense
- *Design Guidelines. Earthquake Resistance of Buildings, Vol. 1,* U.S. General Services Administration Public Buildings Service
- *Earthquake-Resistant Design Requirements Handbook* (H-08-8), U.S. Veterans Administration
- *Installation Handbook for Seismic Support of Water Heaters and Similar Equipment*, Chip O'Neil, Hubbard Enterprises/HOLDRITE

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Expiration date: Continuing education credit will be given for this examination through **November 30, 2019**.

CE Questions — "Seismic Protection of Plumbing Systems" (CEU 265)

1. ________ is the displacement of a building element due to the application of external force.
   a. creep
   b. damping
   c. deflection
   d. oscillation

2. Which of the following parameters must be considered before the exact details and layout of a pipe bracing system can be completed?
   a. weight of pipe and contents
   b. type of structure
   c. location of pipe
   d. all of the above

3. Which of the following is an example of overturning movement?
   a. swinging of hung equipment
   b. excessive foundation rotation
   c. excessive sideways failure of legs
   d. none of the above

4. What is by far the most difficult type of equipment to restrain?
   a. fixed suspended equipment
   b. fixed, floor-mounted equipment
   c. vibration-isolated suspended equipment
   d. vibration-isolated floor-mounted equipment

5. The lateral force is calculated using which of the following?
   a. site coefficient
   b. importance factor
   c. amplification factor
   d. all of the above

6. Which of the following methods would yield the largest cost/benefit ratio in the entire field of seismic protection of plumbing equipment?
   a. vibration isolation
   b. universal base anchorage of equipment
   c. utilizing three pipe-bracing methods
   d. using expansion loops

7. What is the importance factor of a police station?
   a. 1.0
   b. 1.2
   c. 1.4
   d. 1.5

8. Which of the following has proven to be the piping system element most likely to be damaged during earthquakes?
   a. joint
   b. glass pipe
   c. insulation
   d. copper pipe

9. Where the weight of a nonstructural component is greater than or equal to ________ of the effective seismic weight, it shall be designed for a non-building structure.
   a. 15 percent
   b. 20 percent
   c. 25 percent
   d. 30 percent

10. ________ bracing prevents a pipe from moving from side to side.
   a. transverse
   b. longitudinal
   c. diagonal
   d. cross

11. The amplification factor is defined by which of the following?
   a. natural period
   b. damping ratio
   c. mass of equipment and structure
   d. all of the above

12. Mechanical, electrical, and architectural elements of a building are included in which chapter of ASCE/SEI 7?
   a. 12
   b. 13
   c. 15
   d. 17