# Overview of the Seismic Design Process Based on ASCE/SEI 7-22

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Credit: 2 PDH

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# 1 Seismic Design Process

Current U.S. building codes adopt prescriptive seismic design requirements through the adoption of the ASCE/SEI 7 Standard, Minimum Design Loads and Associated Criteria for Buildings and Other Structures. ASCE-SEI revises this standard every six years. The current version is the 2022 edition, which will be adopted by the 2024 International Building Code (IBC), the model code for new construction used by most jurisdictions in the United States. This guide describes the criteria contained in ASCE/SEI 7-22 and notes where significant changes relative to the last edition (2016) have occurred.

Figure 1 is a flowchart illustrating the key steps in the building seismic design process, along with references to the chapters in this guide that provide an explanation of fundamental principles associated with the step and applicable ASCE/SEI 7 chapters where the requirements are found.

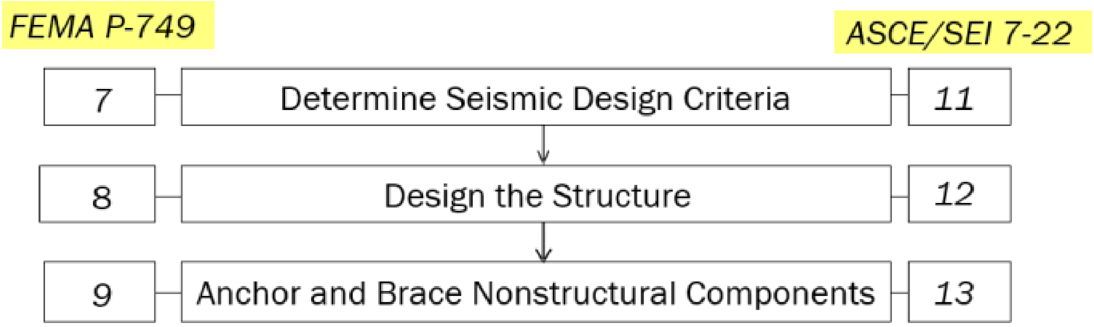


*Figure 1. Seismic design process as outlined in chapters of this guide and ASCE/SEI 7-22*

Determining the seismic design criteria, the first step, consists of identifying the risk category, level of seismic hazard, and seismic design category. Designing the structure, the second step, involves using the criteria from the first step in selecting a structural system, developing a preliminary design, performing analysis to predict the seismic response, ensuring adequate strength and stiffness, and detailing the structure to comply with system-specific requirements. The final step is to design anchorage and bracing for nonstructural components.

ASCE/SEI 7 and this guide focus on design requirements associated with ground shaking, but consideration of other potential earthquake effects like landslide, liquefaction, tsunami, and fault rupture is also important. The existence of other hazards is location-specific, and mitigation of them in design is similarly dependent on individual site conditions, so specific design criteria is not included within ASCE/SEI 7. Rather, ASCE/SEI 7 requires a geotechnical investigation to determine if these hazards exist and that the geotechnical engineer provides recommendations for any necessary mitigation in a report.

Design for other loads (e.g., dead, live, wind) impact the structural design of a building, but are not covered by this guide. ASCE/SEI 7 covers other loading criteria, including load combinations for design.

**Performance-based design** is an alternative approach to the prescriptive design process described in ASCE/SEI 7 and the building codes specifically permit this approach, there is currently no standard for performance-based design of new buildings. However, existing resources can be applied. The section 1.1 provides more information.

**Tsunami design** is required by ASCE/SEI 7-22 for select buildings in tsunami hazard zones. Section 1.2 provides basic information about tsunami-resistant design, but detailed background is outside the scope of this course.

**Soil-structure interaction (SSI)** analysis is not required by ASCE/SEI 7-22, but instructions are provided in the standard, and it is becoming more common in seismic design. Section 1.3 provides basic background on using SSI.

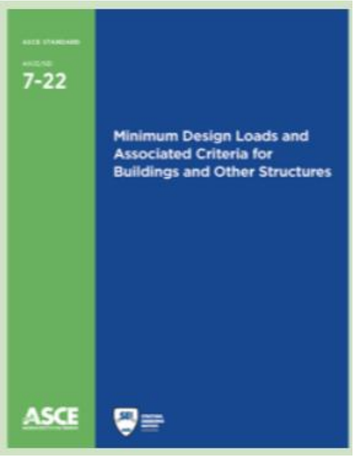
**Energy dissipation and seismic isolation systems** improve the seismic performance of buildings when used but are rare in the United States. Sections 1.4 and 1.5 provide additional information on these systems.

**Nonbuilding structures** are addressed by ASCE/SEI 7-22 and in many cases, similar to the design of buildings. Section 1.6 explains what nonbuilding structures are and in what ways design of them is similar or not similar to buildings.

## Important Resources

**ASCE/SEI 7-22: Minimum Design Loads and Associated Criteria for Buildings and Other Structures**

*This standard describes the design loads and associated criteria to be used in the general design of buildings and other structures. Loads covered include dead, live, seismic, soil, flood, tsunami, snow, rain, atmospheric ice, and wind loads. Published 2022. Available through ASCE.*



7-22

Minimum Design Loads and Associated Criteria for Buildings and Other Structures

ASCE

## 1.1 Performance-based Design

Performance-based design provides engineers an alternative method of seismic design that can result in better performing buildings and allow code-intended performance to be achieved more economically. It can also facilitate the use of features not presently recognized or permitted by the building codes.

For many years, building codes have permitted the use of design procedures and building construction that do not conform to the prescriptive requirements of the building code, provided that the project team can demonstrate to the satisfaction of the Authority Having Jurisdiction (AHJ) that the resulting construction will provide equivalent protection of public safety and welfare. These permissive procedures are called alternative means and methods. Historically, the alternative means and methods approach has been used to introduce new design and construction technologies by demonstrating their use on real projects prior to their adoption by the code in later editions.

The design process under the alternative means and methods approach is as follows:

a) Define and reach agreement as to what performance is appropriate or acceptable
b) Perform a design
c) Test the design under design loadings, either in the laboratory or analytically
d) Determine whether the desired performance can be attained

Performance-based design is an alternative to prescriptive design requirements. It is called performance-based because the design process focuses on defining and verifying the performance that can be obtained. Performance-based designs may or may not actually conform to the prescriptive code requirements but should be capable of providing equivalent or better performance than conforming designs. Today, performance-based design approaches are commonly used for fire/life safety, blast protection, and seismic design.

Performance-based seismic design practices initiated in the 1990s, with the development of FEMA 273/274, Guidelines and Commentary for Seismic Rehabilitation of Buildings, which later evolved into the ASCE/SEI 41 Standard, Seismic Evaluation and Retrofit of Existing Buildings. FEMA 273/274 established a series of standard structural performance levels, as shown in Figure 2, and identified a series of standard performance objectives for existing buildings that paralleled the performance objectives described in commentary to ASCE/SEI 7 for new buildings. In ASCE/SEI 41 vernacular, a performance objective is a statement of a particular performance level to be achieved for a given ground motion hazard level. The recommended performance objectives for new buildings are Collapse Prevention Performance for MCER shaking (Risk-targeted maximum considered earthquake) and Life Safety Performance for DE (Design Earthquake) shaking.

*Figure 2. Standard ASCE/SEI 41 performance levels.*

Because the procedures for alternative means and methods in the building code allow for demonstration of equivalent or superior performance, performance-based design has become the preferred approach for design of buildings to achieve better performance than required by the building code. As an example of this, a corporation may decide that the appropriate performance objectives for a critical data center are Operational Performance for design earthquake shaking and Life Safety Performance for MCER shaking. Formulation of other performance objectives is also possible.

One of the principal advantages of performance-based design approaches is that because all project participants, including the owner/developer, design team, and AHJ, must agree to the performance objectives used as the basis for design, everyone should be clear as to the expected building performance in future earthquakes. This can also become a disadvantage. It is very difficult to precisely predict future earthquake performance of a building which has not yet been constructed. This is because each earthquake produces unique ground motions and each ground motion has different effects on buildings; our methods of analyzing buildings are approximate; the strengths of construction materials are highly variable; contractors are allowed tolerances in their construction; and the building condition may deteriorate over time. Given these uncertainties, there is significant potential that a building designed to a particular objective will perform worse than implied by the objective, leading to post-earthquake litigation and disputes.

Another significant disadvantage to the ASCE/SEI 41 methodology is that when selecting performance objectives, many owners desire information on the repair costs, repair times, and other consequences associated with their performance objective selection. The ASCE 41 performance levels relate only qualitatively to these important consequences.

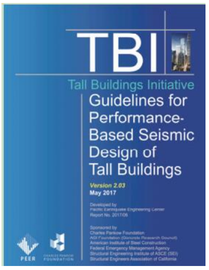
In response to these issues, FEMA funded the development by ATC of the FEMA P-58 series, Next Generation Performance-based Seismic Design Methodology. FEMA P-58 expresses performance as the probability of incurring earthquake-induced casualties, repair costs, repair times, and other consequences. First published in 2010, FEMA P-58 is seeing expanded use in building design. It is also being used to explore potential improvements to the building code design requirements.

As the FEMA P-58 methodology was being evaluated, the Pacific Earthquake Engineering Research (PEER) Center, one of three NSF-funded national earthquake engineering research centers, developed its TBI Guidelines for Performance-based Seismic Design of Tall Buildings to provide engineers an alternative means of designing more reliable high-rise structures. The PEER TBI Guidelines offer a hybrid approach between the ASCE/SEI 41 and FEMA P-58 methodologies. Specifically, the PEER TBI Guidelines provide a methodology that enables engineers to design for the ASCE/SEI 41 performance objective of Collapse Prevention Performance for MCER shaking with 90% confidence. The procedures embedded in the PEER TBI Guidelines have become the preferred approach for the seismic design of buildings in the Western United States and have also influenced the development of ASCE/SEI 7 Chapter 16, Nonlinear Response History Analysis. More recently still, ASCE published a prestandard for performance-based wind design.

**Important Resources:**

1) **PEER TBI Guidelines for Performance-Based Seismic Design of Tall Buildings**

*This document provides procedures on performance-based design for earthquake-resistant design of tall buildings, as an alternative to the prescriptive procedures of ASCE/SEI 7. Published 2017.*



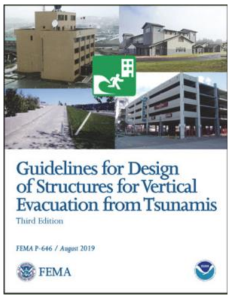
2) **FEMA P-58: Development of Next Generation Performance-Based Seismic Design Procedures for New and Existing Buildings**

*This series, consisting of seven reports, presents the background on performance-based seismic design and guidance for application of the concepts. The methodology utilizes performance measures that can be understood by decision makers, such as the amount of damage, number of potential casualties, loss of use or occupancy, and repair costs. FEMA P-58-7, Building the Performance You Need: A Guide to State-of-the-Art Tools for Seismic Design and Assessment, provides a short introduction to the topic that is clear and approachable for a general audience. Second edition published 2018.*

## 1.2 Design for Tsunami

The 2016 edition of ASCE/SEI 7 introduced criteria for design for tsunami resistance. The tsunami resistant design criteria are applicable only to Risk Category III and IV structures within a tsunami hazard zone. These criteria follow a performance-based approach like that found in the ASCE/SEI 41 Standard, Seismic Evaluation and Retrofit of Existing Buildings.
*** SCE/SEI 7-22 Chapter 6 provides tsunami design criteria.*

**Important Resources:**
***FEMA P-646: Guidelines for Design of Structures for Vertical Evacuation from Tsunamis***
This document addresses guidelines for design against extreme tsunami and earthquake forces, specifically for vulnerable communities along the coast where vertical evacuation is the only alternative. The document provides general information and guidance on determining tsunami hazard, options for vertical evacuation, determination of tsunami and earthquake loads, and the structural design criteria necessary to address these loads. Third edition published 2019.



Guidelines for Design of Structures for Vertical Evacuation from Tsunamis
Third Edition
FEMA P-646 / August 2019
FEMA

## 1.3 Soil-Structure Interaction

Including soil-structure interaction (SSI) in seismic analysis can more accurately predict the behavior of a structure in response to ground shaking. It permits engineers to account for the effect of soil flexibility and energy dissipation potential on response of a structure. This can sometimes result in more economical designs as well as designs that better account for the structural deformation of foundations in response to strong shaking.

Although most seismic analysis performed in support of structural design represents the structure as fixed to the ground, this is a significant simplification. The soils that most structures are founded on are quite deformable and have only modest strength. There are several important consequences of this. First, the very presence of the structure and its foundations affects the motion of the ground, in much the same way that the presence of a boat in water affects the motion of the water immediately surrounding the boat. Pairs of strong motion instruments with one placed on a foundation of the building and the other nearby but in the free field confirm that the shaking at the building is often different and less intense than that experienced in the free field. This is significant because the ground motion prediction models used by the USGS to develop the design ground motion database are based on both free-field and in-structure instruments and accounts for these effects in only a general manner.

Another important aspect of the deformability of soils is that rather than being fixed at their bases, most structures can be more properly viewed as being mounted on a series of vertical, horizontal, and rotational nonlinear springs, and dashpots. The effect of these springs and dashpots is to increase the effective fundamental period of vibration, change the mode shapes, and add damping to the response, as the structure will radiate some of the imposed energy from the earthquake back out into the surrounding soils.

SSI is a means of accounting for these effects and is permitted under the requirements of ASCE/SEI 7 Chapter 19. SSI can take many forms. In its simplest form, the engineer models spring at the base of the structure to represent the flexibility of the soil and the effects this has on the modal properties and response of the structure. In its most complex form, engineers can represent the soils underlying a structure as nonlinear finite elements, just as the structure is modeled, and propagate earthquake energy up to the structure through the soil elements from the bedrock. It is also possible to perform such analysis in steps, first using a very detailed representation of the soil, with the mass and stiffness of the structure represented simply to account for the modification that occurs to the ground motion, and then analyzing the structure for the modified ground motions. ASCE/SEI 7 Chapter 19 also presents simpler procedures that permit closed form solution of period lengthening and damping increment effects.

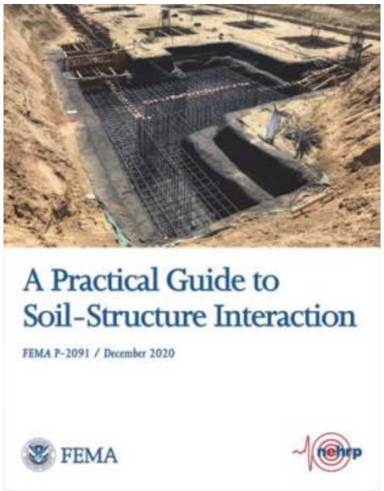
Although use of SSI is not required by the code, it has been used for many years in the design and evaluation of nuclear structures and seismic evaluation and retrofit of buildings. Recently, use of SSI has become more common for design of new structures.

*** ASCE/SEI 7-22 Chapter 19 provides soil-structure interaction criteria*

**Important Resources**

***FEMA P-2091: A Practical Guide to Soil-Structure Interaction***

This guide walks engineers through determining when soil-structure interaction (SSI) effects are of importance and how to implement them in design. Information regarding SSI as implemented in code provisions is presented in an easy-to-follow and concise format, along with examples of applying SSI effects in design. Published 2020.



A Practical Guide to Soil-Structure Interaction

FEMA P-2091 / December 2020

FEMA

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## 1.4 Energy Dissipation Systems

Energy dissipation systems can be used to modify the response of a structure to ground shaking and minimize damage. This technology was first introduced into the building codes in the 1980s and has uses in both design of new construction and retrofit of existing structures. Use of an energy dissipation system does add cost to the project, both for design and construction. As a result, its use in the United States has been limited. Energy dissipation systems and seismic isolation (Section 1.5) have seen widespread application in Japan and some other countries.

Section 2 describes how damping, or energy dissipation, reduces the spectral amplitude of shaking a structure will experience in an earthquake, effectively reducing the intensity of earthquake shaking the structure experiences. Damping is classically expressed as the velocity-dependent term $c$ in the equation of motion (Equation 1) and is typically expressed as the percent of critical damping present in a structure. Figure 7 illustrates the free vibration an SDOF structure with 5% of critical damping would experience if displaced and then released. A structure with 100% of critical damping would come to rest in one cycle of motion.

All real structures have some inherent damping present. The energy dissipation associated with this damping occurs because of minor cracking of concrete and masonry, slippage in bolted connections of steel structures, working of nails in wood structures, and similar behaviors in nonstructural elements such as cladding, interior partitions. The amount of inherent damping structures will exhibit is dependent on how much deformation the structure is undergoing, with larger damping occurring under larger amplitude motion.

Another form of damping that is important to seismic response is hysteretic damping. Hysteretic damping occurs when a structure undergoes inelastic response, such as yielding of beams in flexure or braces in tension. The strain energy that occurs as these elements yield dissipates energy and produces damping.

The building code assumes that structures responding to design earthquake shaking will exhibit 5% of critical damping through a combination of inherent and hysteretic damping and the design spectra used to determine required seismic design forces are 5%-damped spectra.

Several types of dampers are available that can enhance the effective damping of a structure.

- Fluid viscous dampers are similar to automotive shock absorbers. They consist of a double acting hydraulic cylinder that dissipates energy by moving a piston device through a viscous fluid that is contained within an enclosed cylinder.

- Friction dampers are essentially structural braces that are spliced to the structure using slotted holes and high-strength bolts with a tactile material on the mating surfaces of the connection. When the braces are subjected to tension or compression forces, they slip at the splice connection and dissipate energy through friction.

- Wall dampers are a form of viscous damper that consists of vertical plates arranged in a sandwich configuration with a highly viscous material. One set of plates is attached to one level of a structure and another set to the adjacent level. When the structure displaces laterally in response to earthquake shaking, the plates shear the viscous material and dissipate energy.

- Hysteretic dampers dissipate energy by yielding specially shaped structural elements that are placed in series with conventional wall or brace elements.

- Tuned mass dampers consist of a large mass on a spring-like device. When they are mounted on a structure, the lateral displacement of the structure excites the mass, which then begins to move and dissipate significant portions of the energy of the earthquake, protecting the structure in the process.

The most common dampers are of the fluid viscous type, illustrated in Figure 3. The fluid viscous damper consists of a double-acting hydraulic cylinder in which a piston, with specially machined orifices moves through a viscous fluid constrained by an outer casing. The edge of the piston is attached with a strut to one part of the structure, in the case of the illustration, a beam-column joint, and the casing is attached with a strut to another part of the structure. As the structure drifts, in response to earthquake shaking the piston is dragged through the viscous fluid, dissipating energy in the form of heat.

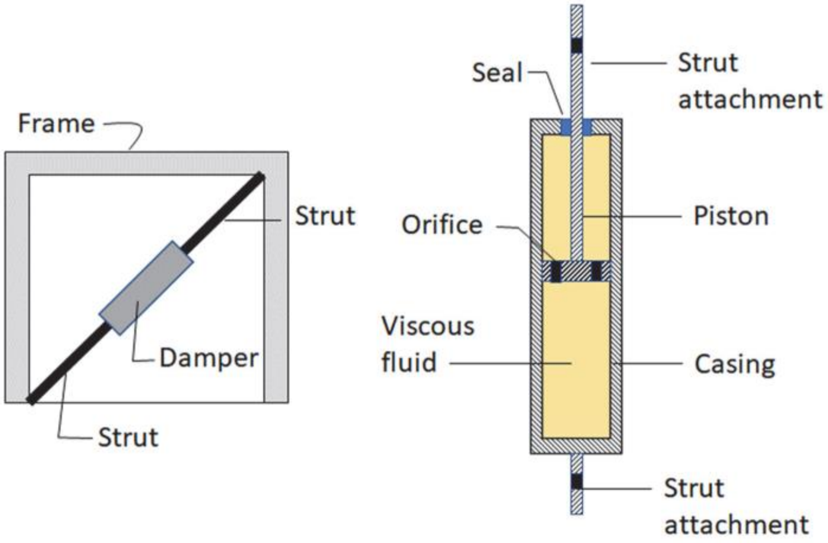

*Figure 3. Fluid viscous damper assembly in frame*

ASCE/SEI 7 Chapter 18 specifies the criteria for design of structures with energy dissipation systems. This requires that in addition to the energy dissipation system, the structure must also have one of the seismic force-resisting systems permitted by Chapters 12 or 15 of ASCE/SEI 7 for the SDC. Analysis can use ELF, modal response spectrum analysis, or nonlinear response history analysis techniques. In the ELF and modal response spectrum approaches, the base shear force is permitted to be reduced up to 25% depending on the amount of damping provided. The chapter includes procedures to compute the amount of damping provided, based on the computed spectral response of the structure, and the characteristics of the damping devices. In nonlinear response history analysis, the damping devices are directly modeled to simulate their effect on the response of the structure.

Since few engineers are familiar with how to design using damping technology, ASCE/SEI 7 requires independent design peer review when energy dissipation systems are used for seismic force resistance. ASCE/SEI 7 also requires rigorous manufacturing quality assurance procedures for the production of energy dissipation devices to ensure that the damping properties assumed in design can be obtained and that the devices are capable of accommodating design earthquake shaking.

## 1.5 Seismic Isolation Systems

Seismic isolation is a method of altering the response of a structure by inserting deformable bearing elements in the vertical load-carrying system of the structure to significantly affect the structural stiffness and fundamental period of response, as well as add energy dissipation or damping. Most commonly, seismic isolation bearings are placed at the base of the structure, between the columns (or bearing walls) and the supporting foundations, or subgrade structure. For this reason, seismic isolation has often been termed base isolation.

Two basic types of isolation bearings are commonly used: elastomeric and sliding. Figure 4 illustrates top, side, and deformed views of a typical elastomeric bearing. The bearings consist of thick steel top and bottom plates, sandwiching and bonded to a laminate consisting of multiple layers of either natural or synthetic rubber and steel plates. The rubber laminations provide the isolator flexibility and an ability to deform laterally by as much as three times the bearing height, as illustrated in the deformed view. The steel laminations provide volumetric stability for the rubber and enable it to withstand vertical loads without excessive vertical displacement. The lateral stiffness of the bearing enables it to return to its neutral position when lateral forces are released. Some elastomeric bearings have a solid lead core within the laminated steel-rubber layers to provide additional damping.

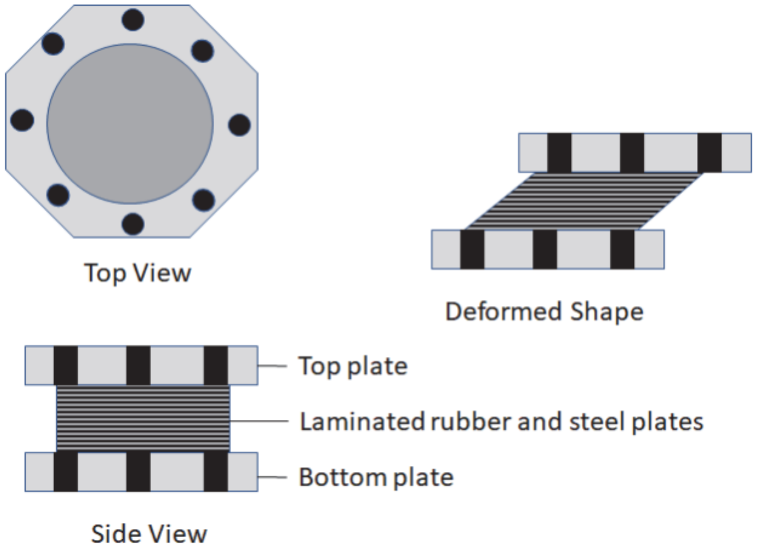

*Figure 4. Elastomeric isolator*

Figure 5 illustrates the concept for a common sliding-type bearing, also known as a friction pendulum. In this bearing type, the bottom plate is machined with a curved surface and coated with a low friction, wear-resistant material. The top plate is attached to an articulated bearing system consisting of a semi-spherical bearing trapped by a machined plate, with all surfaces similarly coated with friction-resistant materials. When lateral forces act on the bearing, the upper plate slides relative to the lower plate. The amount of resistance provided is a function of the curvature of the curved coated surface on the lower bearing, the friction coefficient of the surface preparation and the vertical weight on the bearing.

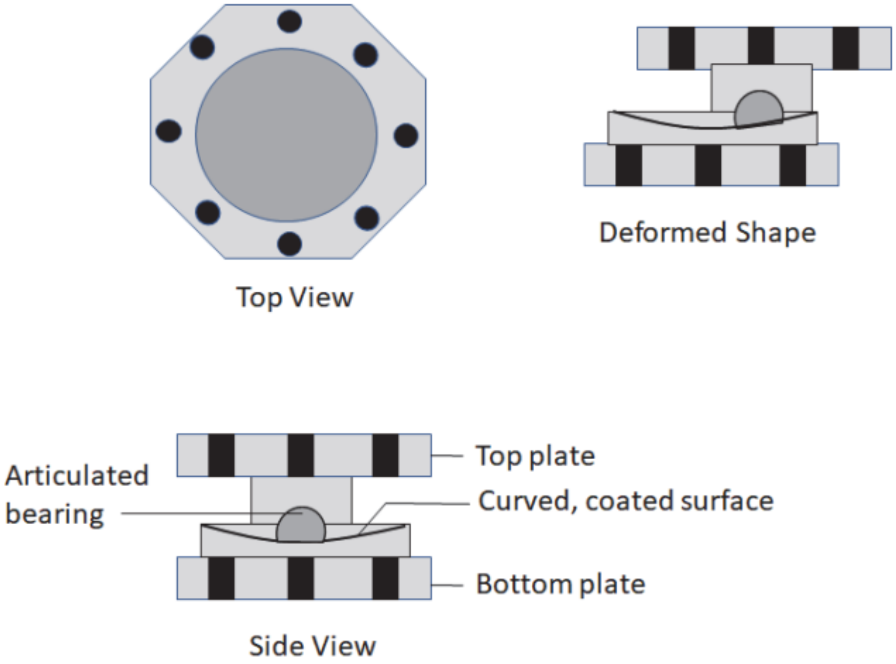

*Figure 5. Sliding-type isolation bearing.*

Essential elements of seismic isolation systems include the bearings themselves, a rigid diaphragm above the isolators to enable the structure to move as a unit on the bearings, and a robust foundation system capable of resisting the sliding and overturning forces. The structure above and below the isolation bearing must be designed to withstand the substantial P-delta effects associated with large lateral displacements of the bearings, which can be on the order of 24 inches or more. Elastomeric type bearings distribute half of the P-delta associated moments to the structure above and half to that below. Sliding-type bearings distribute all of the P-delta moments to the structure beneath the bottom plate.

Another important consideration in the design of seismically isolated structure is that all the building elements that cross the plane of isolation, including electrical lines, plumbing, cladding systems, and HVAC ducts, must be designed, and installed to accommodate the relative displacements of the structure across the isolation plane.

The design criteria are similar to that of damping systems and involves determining the effective natural period of the isolated structure, as well as the damping of the isolation system.

The superstructure must be designed using small values of the response modification coefficient, *R*, so that inelastic behavior of the superstructure is limited and most deformation occurs in the isolators themselves.

Seismic isolation is one of the most effective methods of protecting structures from the effects of earthquakes and is ideal for use in structures that can tolerate little damage to the structure, its mechanical and electrical systems, or its contents. For these reasons, it is most used in the United States for hospitals, data centers, and museums. It is also commonly used as a means of retrofitting historically important structures constructed of archaic and fragile systems, without extensive structural modifications to the historic structure.

*****ASCE/SEI 7-22 Chapter 17 specifies the criteria for design and manufacture of seismic isolation systems.***

## 1.6 Nonbuilding Structures

The building code also includes seismic design criteria for many types of structures that are not buildings. These structures are called nonbuilding structures and include:

- Storage tanks, pressure vessels, and pipe supports such as those commonly found in petroleum refineries and chemical plants (Figure 6),
- Water towers,
- Chimneys and smokestacks,
- Steel storage racks (Figure 7),
- Piers and wharves,
- Amusement structures including roller coasters, and
- Electrical transmission towers.

*Figure 6. Structures commonly found in petroleum refineries and chemical plants.*

*Figure 7. Seismic design criteria for steel storage racks of the type used in large warehouses and big-box retail stores are included in the building code.*

ASCE/SEI 7 identifies four different types of structures and specify somewhat different design requirements for each:

- Buildings,
- Nonbuilding structures similar to buildings,
- Nonbuilding structures not similar to buildings, and

- Nonbuilding structures supported by other structures

The primary difference between buildings and nonbuilding structures similar to buildings is that buildings are designed with the intent that they will be occupied and provide shelter to occupants, while nonbuilding structures are not. Because most buildings are occupied, they are typically enclosed, and have uniform distribution of story heights and weight. Nonbuilding structures are often used in industrial applications and are configured to suit their industrial uses. They often are unenclosed, support large concentrations of weight (e.g., large pressure vessels, and heavy rotating equipment such as compressors or electrical generators) and must be designed to resist cyclic and thermal forces from the processes they support. These design criteria often result in structures that use much larger members and are much stronger than is typical of buildings. Over many years, engineers have observed that structural features that have resulted in poor performance in buildings, have not been a problem in nonbuilding structures similar to buildings. Given this, and the reduced occupancy associated with most nonbuilding structures, ASCE/SEI 7 specifies similar design procedures but different criteria for the design of buildings and nonbuilding structures similar to buildings. The requirements for seismic design of building structures are contained in Chapter 12 of ASCE/SEI 7 while that for nonbuilding structures similar to buildings is contained in Chapter 15.

Most of the design requirements for nonbuilding structures similar to buildings are the same as those for buildings. However, the limitations on structural systems associated with SDC, and the required design forces are relaxed relative to the criteria for buildings. Table 15.4-1 (Chapter 15 of ASCE/SEI 7) presents the system limitations, $R$, $Cd$, and $\Omega_o$ coefficients applicable to such nonbuilding structures.

Nonbuilding structures not similar to buildings include mechanical and electrical equipment items with structural support systems that are integral to the function of the equipment. Examples include ground-supported tanks, elevated tanks, pressure vessels, cooling towers, electrical transmission towers, and chimneys and stacks. The design requirements for many of these highly specialized structure types are contained in design standards developed by industry associations such as the American Petroleum Institute and American Water works Association. Rather than transcribing the requirements contained in these standards, ASCE/SEI 7 specifies seismic design criteria for these structures through reference to the industry standards, sometimes with specification as to how ground motions are to be derived and other limits.

Nonbuilding structures supported by other structures are typified by small penthouse structures housing mechanical equipment, mounted on top of buildings or other structures. These are designed similar to nonbuilding structures similar to buildings, with the exception that the ground shaking level used to design the structure is based on the motion transmitted by the supporting structure.

Some nonbuilding structures, however, are not covered by the design recommendations contained in the building codes because they are of a highly specialized nature and industry groups that focus on the design and construction of these structures have developed specific criteria for their design. Some such structures are highway and railroad bridges, nuclear power plants, hydroelectric dams, and offshore petroleum production platforms.

***Note: ASCE/SEI 7-22 Chapter 15 provides design requirements for nonbuilding structures***

## Background

Figure 8 portrays a simple, elastic structure consisting of a lumped mass, $m$, mounted on top a single column element, having lateral stiffness, $k$. Such structures are termed single degree of freedom (SDOF) systems. If pulled to the side to an initial displacement and released, as illustrated in the figure, the mass will oscillate about its zero-deflection point, slowing with time, and eventually come to rest. The amount of time it takes for the mass to make one complete oscillation, from a position of maximum displacement in one direction, back through the zero-deflection point, to maximum displacement in the reverse direction and back again, is called the period of the structure, Period is represented by the symbol $T$. For SDOF structures, like that shown in Figure 8, the period, $T$, has a value given by the expression $2 \pi \sqrt{m} /k$ , which, in the case of the structure in Figure 8, is one second. The amount of degradation in peak amplitude that occurs from one cycle of motion to the next is a measure of the amount of damping, or energy dissipation, that is occurring.

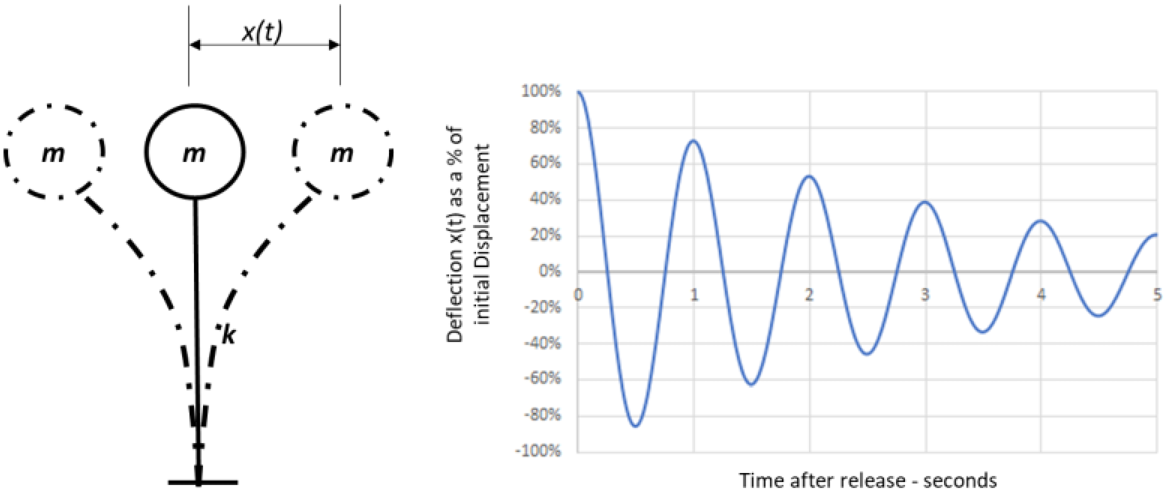

*Figure 8. Dynamic behavior of an SDOF structure.*

If this simple structure is subjected to earthquake ground motion, the ground will displace from underneath the structure, as illustrated in Figure 9, and the mass will tend to stay at rest due to its inertia. Because the column has been deformed by the moving ground and has stiffness, *k*, the column will impose a force, *kx*, on the mass, which will then accelerate towards the position of the displaced ground and then oscillate. However, in an earthquake, the ground is continuously moving, and deforming the structure, causing a time-variant force on the mass with the mass moving in an apparently chaotic manner.

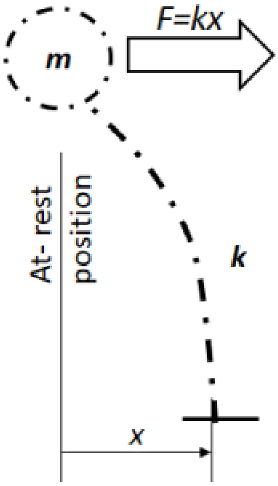

*Figure 9. Ground motion effect on structure*

The response of this simple structure to earthquake shaking is measured in terms of the time-varying lateral deformation between the mass and its base, $x(t)$; and the time-varying amount of force, $F(t)$, experienced by the structural element supporting the mass, both resulting from the response of the structure to the motion of the ground, represented as the time varying acceleration function $\ddot{u}(t)$.

The force and displacement experienced by the structure in responses to a specific ground motion (Figure 10) can be obtained by the stepwise numerical solution of the equation of motion for the structure:

$$m(\ddot{x}(t) + \ddot{u}(t) + c\dot{x}(t) + k(x)x(t)) = 0$$ ---------------- EQ(1)

where:

$\ddot{x}(t)$ = velocity of the mass at time $t$, relative to its base

$\dot{x}(t)$ = acceleration of the mass at time $t$, relative to its base

$c$ = ability of the structure to dissipate earthquake energy, known as damping

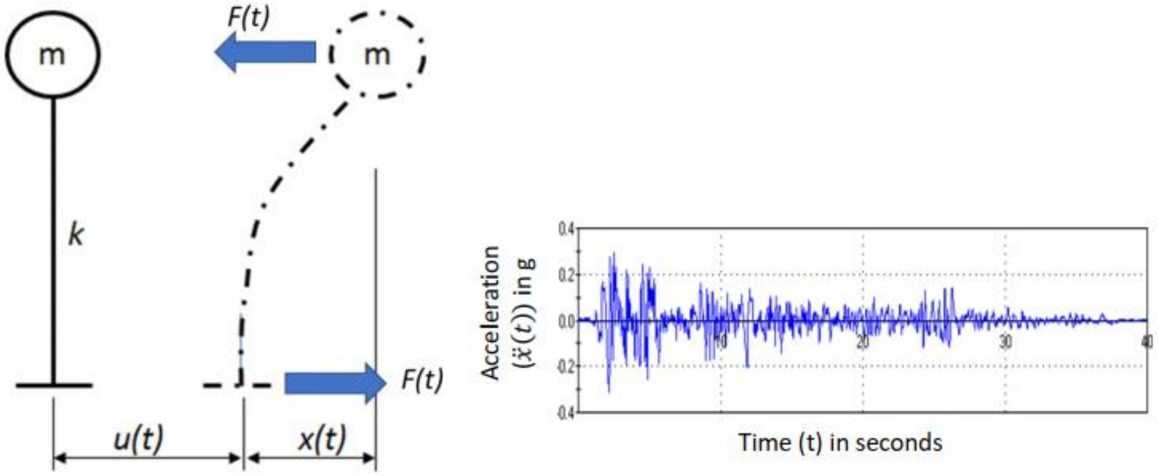

*Figure 10. SDOF structure subjected to ground motion*

Figure 11 is a plot of the displacement response, which is the value of $x$ as a function of time for the simple structure and ground motion shown in Figure 10. The structure exhibits a series of degrading sinusoidal responses at its fundamental period of one second each time the ground motion excites the structure significantly, which for this ground motion and structure, happens five times during the earthquake. The force in the structure at time *t* is simply the displacement *x* at time *t*, factored by the stiffness *k*. This structure displays a peak displacement to this ground motion of about five inches, and if it had a stiffness of 1,000 kips per inch, it would experience a peak force *F* of about 5,000 kips.

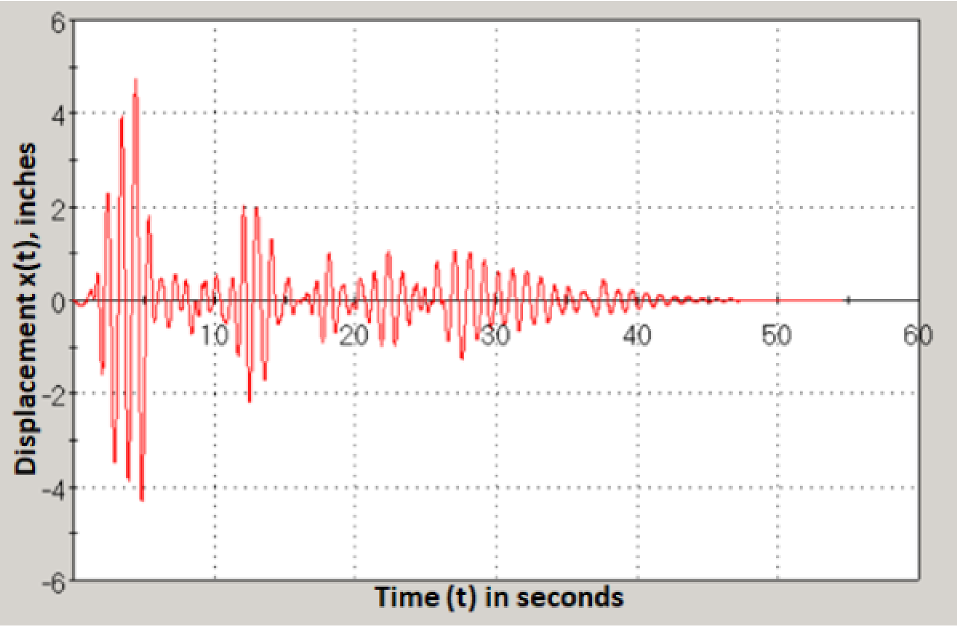

*Figure 11. Displacement response of 1-second SDOF structure to a ground motion.*

Observation of many plots of structural response to earthquake motions have led engineers to understand that earthquake response can be well represented by idealizing the structural response as that of a SDOF system, or series of SDOF systems, having a natural period (or periods) of vibration of the actual structure. This enables use of a simplified method of analysis, called modal response spectrum analysis, that allows engineers to avoid the complex mathematics associated with solving Equation 1, when designing structures.

An acceleration response spectrum is a graphical plot that shows the peak acceleration that SDOF structures having different natural periods, *T*, and specified damping, *c*, would experience if subjected to a specific earthquake motion. Figure 12 is the acceleration response spectrum for the ground motion used in the example shown in Figures 9 and 10. The horizontal axis is the structural period *T*, and the vertical axis is the peak acceleration, termed spectral acceleration, *Sa(T)*, that a structure of period *T* will experience when subjected to this motion.

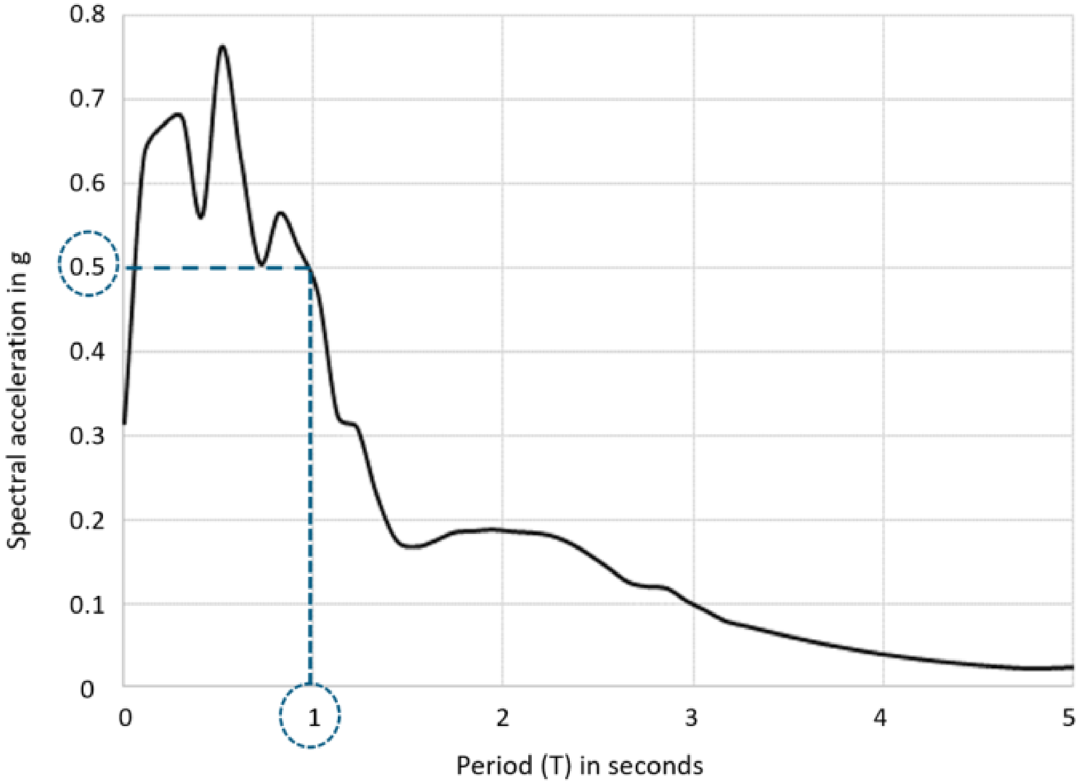

*Figure 12. Acceleration response spectrum for an example ground motion*

If a response spectrum plot for an earthquake motion is available, then the engineer can simply find the spectral acceleration, *Sa(T)*, read off the vertical axis of the response spectra plot at the period of the structure, *T*. For the example SDOF structure having a period *T* of one second and 5% damping, the maximum acceleration that the structure will experience in response to this ground motion is approximately 0.5*g*, where g is the acceleration due to gravity. Once this is known, it is easy to compute the maximum force the structure will experience during this motion using the formula:

$F = S_a(T)W$ -----------(EQ 2)

where $W$ is the weight of the structure. If the example structure has a weight of 1,000 kips, the maximum force it would experience in response to this earthquake motion would be 500 kips ($0.5 \times 1{,}000$ kips).

In Equation 1, the stiffness of the structure, $k(x)$ is expressed as a function of the deformation of the structure, $x$. In the simplest form, the stiffness of the structure has a constant numerical value. Structures that respond in this manner are said to have linear elastic behavior. Such structures will return to their at-rest, undeformed position, once the shaking stops. Such a structure will be undamaged and in the same condition after experiencing the earthquake as it was before. This linear or elastic type of behavior is representative of structural response as long as the force $F$ is less than a limiting value known as the elastic limit.

For reasons of economy and historic precedent, most structures are designed with less strength than would be required to resist design ground motion without damage. Such structures have nonlinear behavior. Instead of having constant stiffness throughout the earthquake, these structures experience a degradation or reduction in stiffness as damage occurs, for example yielding of steel, cracking of concrete and masonry, or slippage of nails in wood structures. There are two significant effects of this damage. First, as the stiffness of the structure decreases, the natural period of the structure, $T$, becomes longer. The second effect is that the damage that occurs dissipates some of the energy of the earthquake, which increases the amount of damping.

Figure 13 illustrates the effect of nonlinear behavior for a hypothetical structure with an initial undamaged period of one second and 5% damping, which because of nonlinear behavior has an effective period of two seconds and effective damping of 20%. In the figure, the plot shown with a solid line is the same 5% damped response spectrum previously shown in Figure 12 and the plot shown with a broken line is the spectrum for this same motion with 20% damping. As shown in the figure, with an elastic period of 1 second, the structure would experience 0.5g of acceleration. However, with an effective (degraded) period of two seconds, and effective damping of 20%, the structure would experience only about 0.12g of acceleration, or roughly one-fifth as much. Since, per Equation 2, the earthquake force on the structure is proportional to the spectral acceleration, this structure would experience roughly one-fifth the force of a similar structure that was strong enough to remain elastic during this motion.

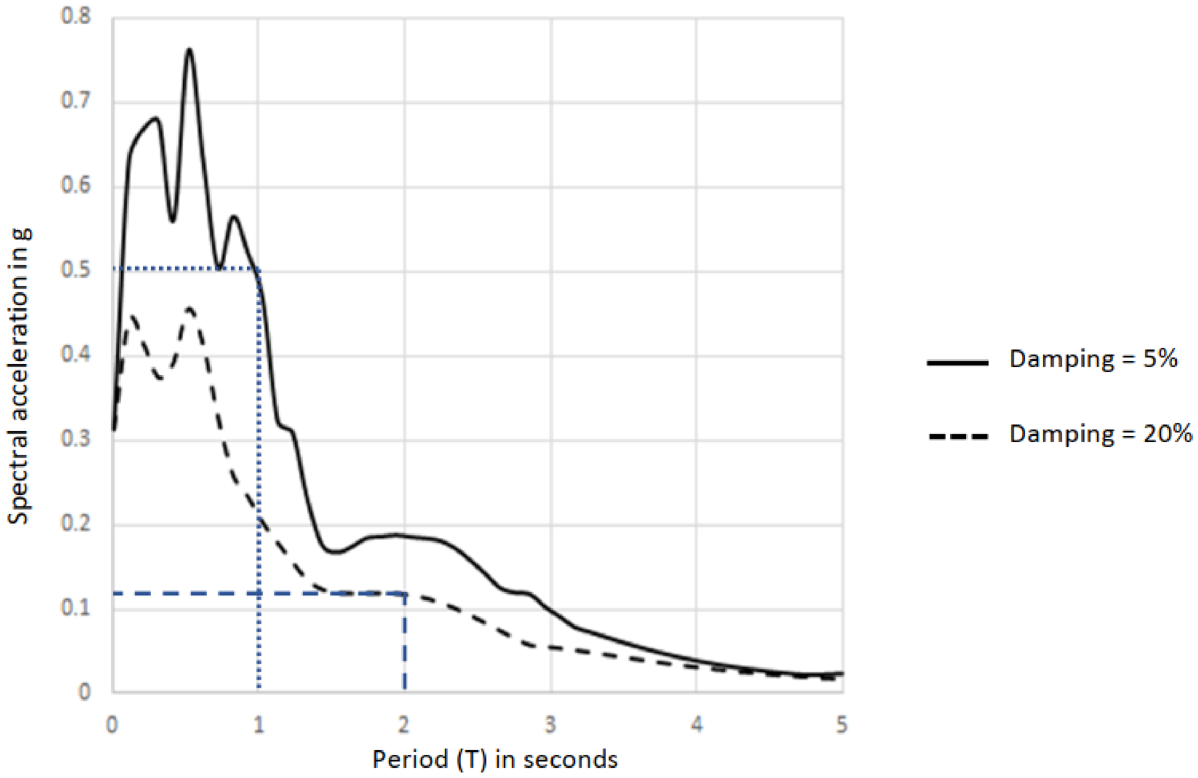

*Figure 13. Illustration of the effect of nonlinear response.*

In the design process, the effects of inelastic response described above is represented by the response modification coefficient, *R*. In the example above, the structure would be assigned an *R* value of 4, and it would be designed for one fourth of the force (1/*R*) required to resist the ground motion without damage (i.e., elastically). The building code designates the value of *R* that can be used, depending on the type of structural system used to resist earthquake forces, the quality of seismic-resistant detailing that is incorporated in the design, and the proven ability of structures of that type to experience nonlinear behavior without collapse.

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