CHAPTER 8

SEISMIC ISOLATION AND ENERGY DISSIPATION SYSTEMS

8-1. Introduction.

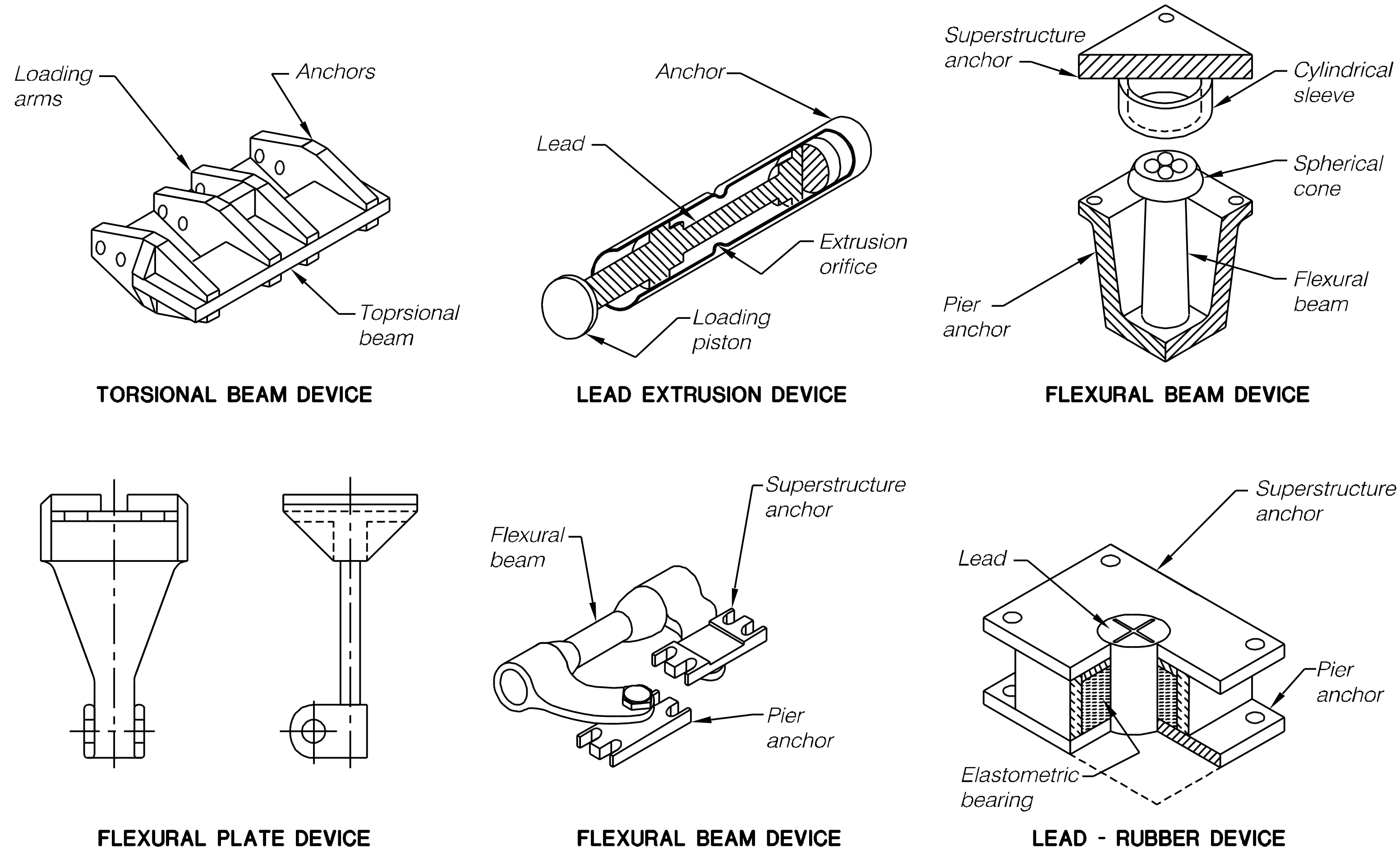
The purpose of this chapter is to provide a brief overview of many new technologies that are rapidly becoming more prevalent in the seismic design of building structures, and to provide guidance for the consideration and evaluation of the use of these systems in selected buildings. These technologies all involve the use of special details or specific devices to alter or control the dynamic behavior of buildings. The structural systems that utilize these technologies can be broadly categorized as passive, active, or hybrid control systems. Definitions of these terms are provided below, although the primary focus of this chapter is on passive control systems. Additional guidelines and design provisions for base isolation systems are provided in FEMA 302. Similar guidance for energy dissipation systems is provided in FEMA 273.

a. System Definitions.

(1) Passive control systems. These systems are designed to dissipate a large portion of the earthquake input energy in specialized devices or special connection details that deform and yield during an earthquake. Since the deformation and yielding are concentrated in the device, damage to other elements of the building may be reduced. These systems are passive in that they do not require any additional energy source to operate, and are activated by the earthquake input motion. Seismic isolation and passive energy dissipation are both examples of passive control systems. Some examples of these devices are presented in Figure 8-1. It is interesting to note that many of these devices can be used at the base of a structure as part of an isolation system, or in combination with braced frames or walls as energy dissipation devices.

(a) Seismic isolation systems. The objective of these systems is to decouple the building structure from the damaging components of the earthquake input motion, i.e., to prevent the superstructure of the building from absorbing the earthquake energy. The entire superstructure must be supported on discrete isolators whose dynamic characteristics are chosen to uncouple the ground motion. Some isolators are also designed to add substantial damping. Displacement and yielding are concentrated at the level of the isolation devices, and the superstructure behaves very much like a rigid body.

(b) Passive energy dissipation systems. The objective of these systems is to provide supplemental damping in order to significantly reduce structural response to earthquake motions. This may involve the addition of viscous damping through the use of viscoelastic dampers, hydraulic devices or lead extrusion systems; or the addition of hysteretic damping through the use of friction-slip devices, metallic yielding devices, or shape-memory alloy devices. Using these systems, a building will dissipate a large portion of the earthquake energy through inelastic deformations or friction concentrated in the energy dissipation devices,



(Note: Reprinted from "Seismic Isolation: History, Application, and Performance - A World View", Spectra, May 1990 with permission from The Earthquake Engineering Research Institute.)

Figure 8-1 Schematic drawings of representative isolation/energy dissipation devices

thereby protecting other structural elements from damage.

(2) Active control systems. These systems provide seismic protection by imposing forces on a structure that counter-balance the earthquake-induced forces. These systems are active in that they require an energy source and computer-controlled actuators to operate special braces or tuned-mass dampers located throughout the building. Active systems are more complex than passive systems, since they rely on computer control, motion sensors, feedback mechanisms, and moving parts that may require service or maintenance. In addition, these systems need an emergency power source to ensure that they will operate during a major earthquake and any immediate aftershocks.

(3) Hybrid control systems. These systems combine features of both passive and active control systems. In general, they have reduced power demands, improved reliability, and reduced cost when compared to fully active systems. In the future, these systems may include variable friction dampers, variable viscous dampers, and semi-active isolation bearings.

b. Mechanical Engineering Applications. It is important to note that the passive energy dissipation systems described here are "new" technologies when applied to civil engineering structures, but have been used in mechanical engineering for many years. There are numerous situations where dampers, springs, torsion bars, or elastomeric bearings have been used to control vibration or alter the dynamic behavior of mechanical systems. Several examples include vehicular shock absorbers, spring mounts that provide vertical vibration isolation for mechanical equipment, and hydraulic damping devices that utilize fluid flow through an orifice to provide shock isolation for military hardware. Many of these devices have been in use for decades and have performed well in situations where they are subjected to millions of cycles of loading; many more than would be required for seismic resistance. The immediate challenge is therefore not to develop new technologies, but to develop guidelines that will enable us to adapt existing technologies to civil/structural engineering applications.

c. Historical Overviews of Building Applications. Several types of isolation and supplemental damping systems have previously been used in building structures to solve problems related to vertical vibrations or wind loading. For example, a building in London is located on isolators in order to damp vibrations from the London Underground; the World Trade Center Towers in New York City were built with a system of viscoelastic dampers in order to alleviate human discomfort due to wind loading. The use of passive energy dissipation systems for seismic design is a relatively recent development, although there are now examples of these systems throughout the world (EERI 1990).

(1) Applications Outside the U.S. Beginning in the early 1970s, a number of bridge structures in New Zealand were constructed using seismic-isolation systems. The first building structure constructed using lead-rubber bearings was a government facility completed in Wellington, New Zealand in 1981. The most widespread use of both seismic isolation and energy dissipation systems is in Japan, where over a hundred structures have been

built using these technologies. Buildings in many countries, including Canada, Mexico, Italy, France, China, England, Russia, Iran, Chile, and South Africa, now use these systems. Facilities with isolation and supplemental damping systems include apartment houses, nuclear power plants, government office buildings, highrises, commercial structures, and monumental historic buildings.

(2) Applications within the U.S. In the United States, many projects are recently completed or under construction. The first new base-isolated building in the U.S. was completed in Rancho Cucamonga, California in 1985; the first seismic upgrade using steel yielding devices was completed in San Francisco, California in 1992. The most recent examples of seismic upgrading by base isolation includes the Oakland, California, City Hall completed in 1997, and the San Francisco City Hall, scheduled for completion in 1999. A number of essential facilities have been built using base-isolation systems, including the Fire Command and Control Facility and the Emergency Operations Center, both in East Los Angeles, California; the Titan Solid Rocket Motor Storage Facility at Vandenburg Air Force Base, California; and the V.A. Hospital in Long Beach, California.

8-2. Design Objectives.

a. General. Passive control systems can be used to achieve different design objectives or performance goals ranging from a life-safety standard to a higher standard that would provide damage control and post-earthquake functionality. The energy dissipation units used in passive control systems are generally simple devices that exhibit stable and predictable inelastic behavior when subjected to repeated cycles of seismic loading. Nevertheless, there is nothing inherent in these devices that guarantees better building performance. The addition of energy dissipation devices will only improve the seismic performance of a building if the devices have been carefully integrated into the seismic design of the structural system, taking into consideration the dynamic characteristics of the building, the dissipators, and the soil at the site.

b. Performance Objectives. Passive energy systems can be used to achieve building performance goals ranging from a life-safety standard to a higher standard that would provide damage control and post-earthquake functionality. The life-safety standard is currently reflected in the minimum design lateral-force requirements of conventional building codes. Damage control and post-earthquake functionality reflect higher performance goals that would provide additional protection from structural and nonstructural damage and loss of function. The discussion below compares how these various performance objectives can be met using either conventional design or passive control systems.

(1) Life Safety Standard. The philosophy embodied in building codes governing conventional fixed-base construction is that structures should resist minor earthquakes without damage; moderate earthquakes with nonstructural but without structural damage; and major earthquakes with structural damage but without collapse. This is often referred to as a life-safety standard, since the objective of these requirements is primarily to prevent loss of life due to catastrophic failures, not to prevent costly damage or loss of function.

(a) Structural Damage to Conventionally Designed Buildings. Based on observations from past earthquakes and laboratory tests, it is assumed that a properly detailed structure, designed to remain elastic for reduced seismic forces, will have sufficient strength and energy absorption capability to resist a major earthquake without collapse. The energy absorption capacity of conventional structural systems is a result of the yielding and degradation, i.e., damage to the structural and non-structural elements of the building. This includes degradation of beam-column joints, buckling of steel braces, cracking of shear panels and interior partition walls, etc. Following a major earthquake, buildings designed to meet the minimum life-safety standard are not expected to be functional, and may not be repairable.

(b) Passive Control Systems. To date, most projects where these technologies have been employed involve structures that were designed to a standard higher than life safety. In the future, these technologies may be useful in providing structures that meet the life safety objectives with lower life-cycle costs than for conventional design, or providing cost-effective seismic upgrades for older construction that does not comply with current life safety requirements.

(2) Damage control and post-earthquake functionality. In order to reduce or avoid damage to structures and building systems, a building's behavior must be investigated for a range of earthquake motions from smaller, more frequent events, to larger, infrequent events. Seismic demands on structural elements, stairs, ceiling systems, cladding, glazing, utilities, computer equipment, piping and mechanical systems, and other critical building components must be reviewed in order to assess the post-earthquake functionality of essential facilities.

(a) Conventional Design. In order to meet restrictive post-earthquake functionality requirements, most conventionally designed buildings must be designed to remain elastic for larger earthquake forces, with less reliance on ductility, increased damping, or significant inelastic behavior.

(b) Passive Control Systems. Seismic isolation and energy dissipation systems offer attractive alternatives to conventional design, since all these schemes can be used to reduce the earthquake input energy and concentrate the inelastic deformations in the isolators or damping devices, protecting critical elements of the structural frame from damage. Isolation and dissipation devices all have a yield threshold, and exhibit elastic behavior below this threshold and inelastic behavior after initial yielding. It is therefore especially important that response to both small and large earthquake motions be investigated, in order to capture the effective range of behavior of the particular device.

8-3. Seismic Isolation Systems.

a. Design Concept. The design of a seismic isolation system depends on many factors, including the period of the fixed-base structure, the period of the isolated structure, the dynamic characteristics of the soil at the site, the shape of the input response spectrum, and the force-deformation relationship for the particular isolation device. The primary objective of the design is to obtain a structure such that the isolated period of the building is sufficiently longer than both the fixed-base period of the building (i.e., the period of the superstructure), and the predominant period of the soil at the site. In this way, the superstructure can be decoupled from the maximum earthquake input energy. The spectral accelerations at the isolated period of the building are significantly reduced from those at the fixed-base period. The resultant forces on structural and nonstructural elements of the superstructure will be significantly reduced when compared with conventional fixed-base design. The benefits resulting from base isolation are attributed primarily to a reduction in spectral demand due to a longer period, as discussed in this Paragraph. Additional benefits may come from a further reduction in the spectral demand attained by supplemental damping provided by high-damped rubber components or lead cores in the isolation units. A preliminary evaluation of these benefits requires the following considerations:

(1) Select a target base shear, V_S, and an appropriate response modification factor, R_I, for the isolated building. Calculate $K_{D\max}\, D_D$ from Equation 8-8.

(2) From test data supplied by the isolation manufacturer, select units with effective stiffnesses $K_{D\min}$ and $K_{D\max}$ that approximately satisfy the calculated value of $K_{D\max}\, D_D$.

(3) From the isolator damping characteristics provided by the manufacturers, assume an effective damping coefficient, $\$_D$, and obtain the appropriate value of B_D from Table 8-1.

(4) Calculate the design displacement, D_D, using Equation 8-1. Compare the calculated value with the assumed value, and if necessary, reiterate the process with revised values of $K_{D\max}$, T_D, and B_D until isolator properties provide the desired base shear, V_S, in the building.

(5) Calculate maximum displacement, D_M, using Equation 8-3 and total maximum displacement, D_{TM}, using Equation 8-6. The isolated building and all connecting utilities and appurtenances must be able to accommodate these displacements without interference.

b. *Device Description.* A number of seismic isolation devices are currently in use or proposed for use in the U.S. Although the specific properties vary, they are all designed to support vertical dead loads and to undergo large lateral deformations during a major earthquake. Some of these systems use elastomeric bearings; others use sliding systems that rely on frictional resistance.

Table 8-1

Damping Coefficient, B_D or B_M

Effective Damping, $\$_D$ or $\$_M$ (Percentage of Critical)[a,b]	**B_D or B_M Factor**
$\leq$ 2%	0.8
5%	1.0
10%	1.2
20%	1.5
30%	1.7
40%	1.9
$\geq$ 50%	2.0

a The damping coefficient shall be based on the effective damping of the isolation system determined in accordance with the requirements of Paragraph 8-3k.

b The damping coefficient shall be based on linear interpolation for effective damping values other than those given.

(1) Elastomeric Systems.

c. Applications. While base isolation is an ideal solution for some building structures, it may be entirely inappropriate for others. Since the objective of isolation design is to separate the response of the fixed-base structure from the predominant period of the underlying soil, it is most effective when these two periods coincide. In cases where they are already widely separated, base isolation may increase the response of the structure rather than reducing it. For instance, a very stiff structure on very soft soil would be a poor candidate, as would a very soft structure on very stiff soil. This is shown in Figures 8-2, 8-3, and 8-4 using three representative building types and three different soil types, represented by earthquake response spectra. The damping of the isolation devices may serve to further reduce the response of the building, but for the sake of simplicity, the effect of damping is not included in the following examples.

(1) Hard soil example. Three fixed-base structures are considered as potential candidates for isolation. The period of the isolated structure for all three cases is assumed to be 2.5 seconds. The three buildings, and fixed-base periods without isolators, are as follows:

- Concrete shear wall or steel braced frame building; T = 0.3 seconds;

- Concrete frame building; T = 0.7 seconds;

- Steel frame building; T = 1.2 seconds;

From Figure 8-2, it is evident that the seismic forces would be significantly reduced for the 0.3- and 0.7-second-period structures, and reduced by a smaller amount for the more flexible building with the 1.2-second period. It is important to remember that using conventional design principles, all three of these structures would soften during a major earthquake, and the forces would consequently be reduced, even without the addition of isolators. Nonetheless, these structures would be damaged, and if damage control and post-earthquake functionality are important issues, then isolation may still be useful even for the more flexible steel frame structure.

(2) Soft soil example. The same three fixed-base structures are considered as potential candidates for isolation. The period of the isolated structure for all three cases is assumed to be 2.5 seconds. From Figure 8-3, it may appear that none of the three buildings are good candidates for base isolation. The responses of the 0.7- and 1.2-second-period structures are reduced at a period of 2.5 seconds, but not dramatically. The response of the 0.3-second-period building would increase; nevertheless, the 0.3-second fixed-base structure would soften during a large earthquake, resulting in higher seismic forces and additional damage. Thus, if post-earthquake functionality is important, all of these structures might benefit from an appropriate isolation system.

(3) Very-soft-soil example. In this case, all three structures shown in Figure 8-4 would be subjected to higher seismic forces at the isolated period than at the fixed-base period, and no advantage would be gained from base isolation.

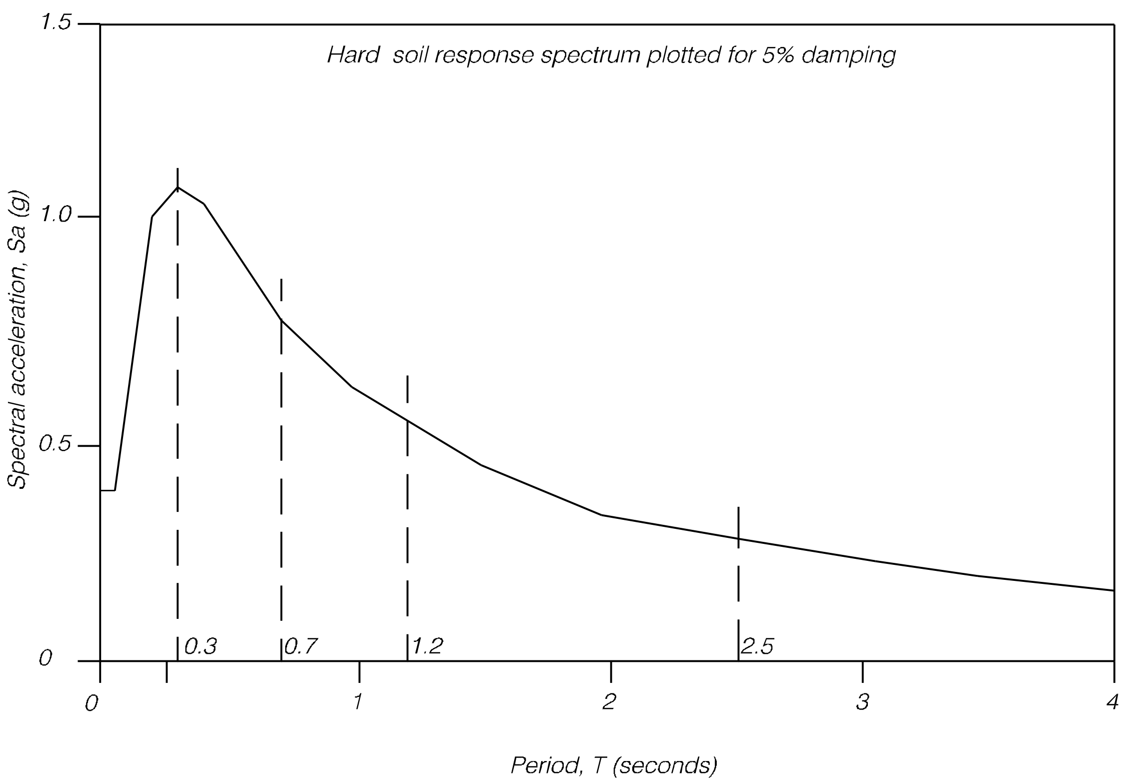


Figure 8-2 Seismic isolation hard soil example

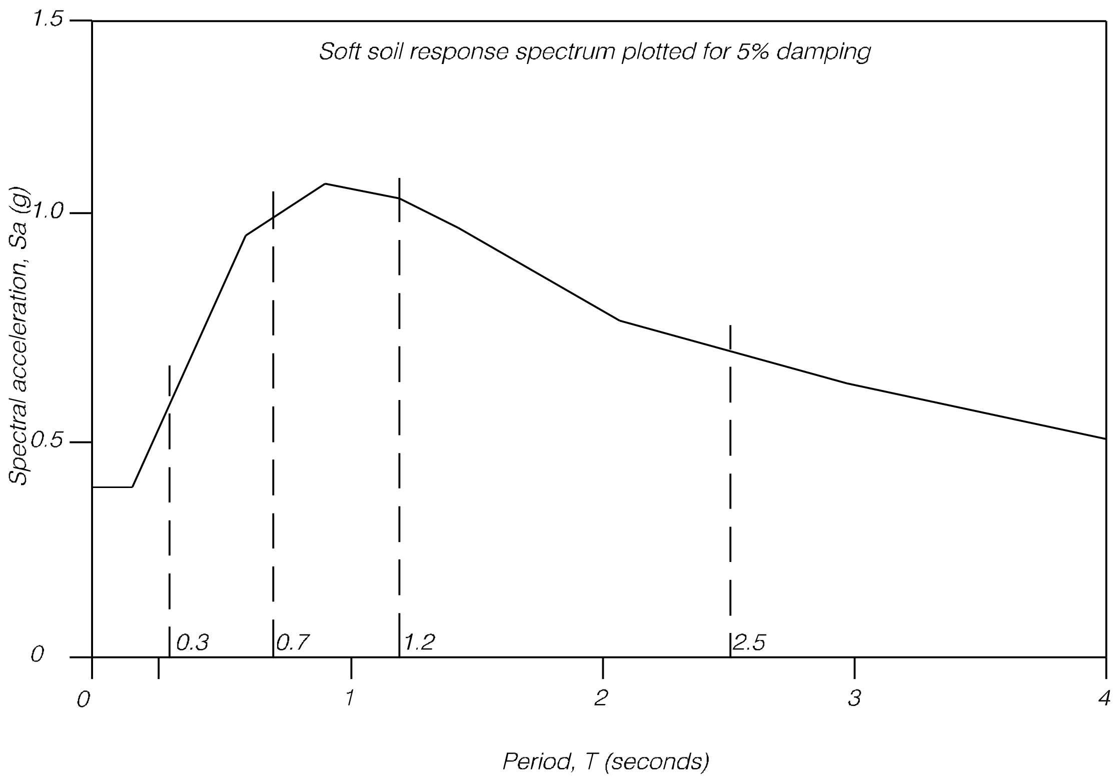


Figure 8-3 Seismic isolation soft soil example

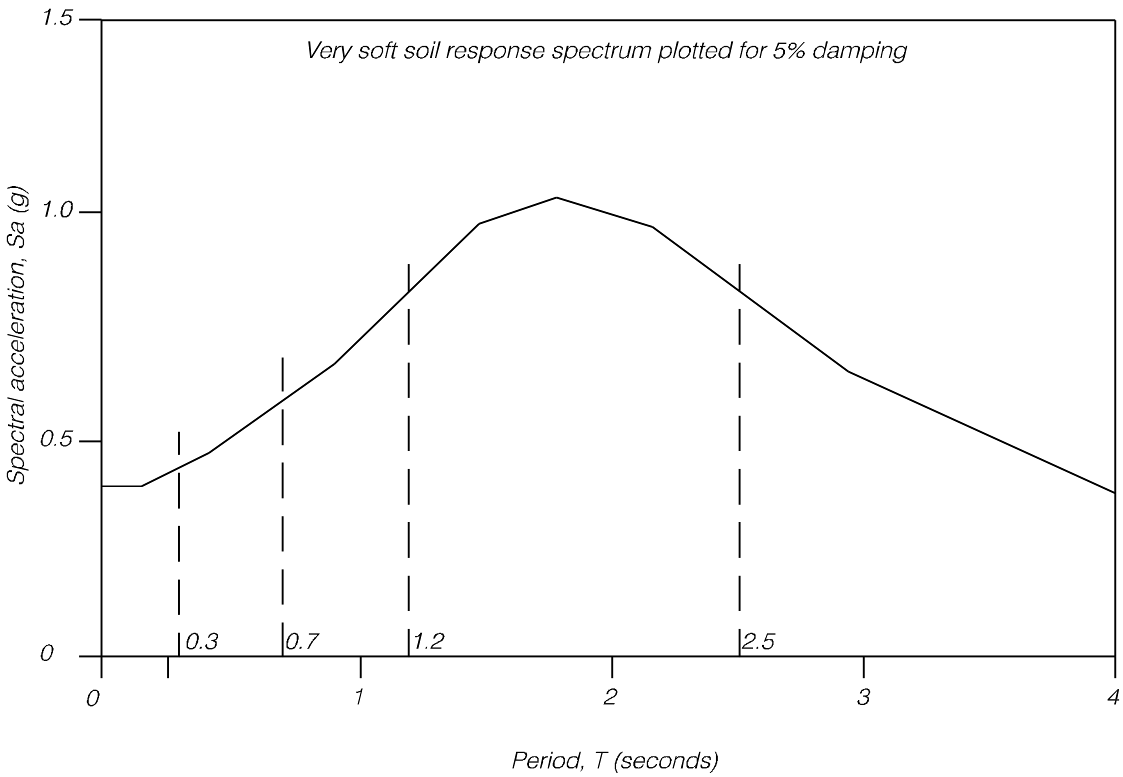


Figure 8-4 Seismic isolation very soft soil example

d. Design Criteria.

(1) Basis for design. The procedures and limitations for the design of seismically isolated structures shall be determined considering zoning, site characteristics, vertical acceleration, cracked section properties of concrete and masonry members, Seismic Use Group, configuration, structural system, and height in accordance with Section 5.2 of FEMA 302, except as noted below.

(2) Stability of the isolation system. The stability of the vertical-load-carrying elements of the isolation system shall be verified by analysis and test, as required, for lateral seismic displacement equal to the total maximum displacement.

(3) Selection of analytical procedure.

(a) General. Any seismically isolated structure is permitted to be designed using the dynamic lateral response procedure of Paragraph 8-3f, as are certain seismically designed structures defined below.

(b) Equivalent lateral-force procedures. The equivalent lateral-response procedure of Paragraph 8-3e is permitted to be used for design of a seismically isolated structure, provided that:

1. The structure is located at a site with S_1 less than or equal to 0.60g;

2. The structure is located on a Class A, B, C, or D site;

3. The structure above the isolation interface is not more than four stories or 65 feet (20 m) in height;

4. The effective period of the isolated structure, T_M, is less than or equal to 3.0 sec.;

5. The effective period of the isolated structure, $T_{D,}$ is greater than three times the elastic, fixed-base period of the structure above the isolation system, as determined by Equations 5.3.3.1-1 or 5.3.3.1-2 of FEMA 302;

6. The structure above the isolation system is of regular configuration; and

7. The isolation system meets all of the following criteria:

- The effective stiffness of the isolation system at the design displacement is greater than one-third of the effective stiffness at 20 percent of the design displacement;
- The isolation system is capable of producing a restoring force as specified in Paragraph 8-3i(2)(d);
- The isolation system has force-deflection properties that are independent of the rate of loading;
- The isolation system has force-deflection properties that are independent of vertical load and bilateral load; and

- The isolation system does not limit maximum capable earthquake displacement to less than S_{M1}/S_{D1} times the total design displacement.

(c) Dynamic analysis. A dynamic analysis is permitted to be used for the design of any structure, but shall be used for the design of all isolated structures not satisfying Paragraph 8-3d(3)(b). The dynamic lateral response procedure of Paragraph 8-3f shall be used for design of seismically isolated structures as specified below.

1. Response-spectrum analysis. Response-spectrum analysis is permitted to be used for design of a seismically isolated structure, provided that:

- The structure is located on a Class A, B, C, or D site; and

- The isolation system meets the criteria of Item 7 of Paragraph 8-3d(3)(b).

2. Time-history analysis. Time-history analysis is permitted to be used for design of any seismically isolated structure, and shall be used for design of all seismically isolated structures not meeting the criteria of Paragraph 1 above:

3. Site-specific design spectra. Site-specific ground-motion spectra of the design earthquake and the maximum considered earthquake developed in accordance with Paragraph 8-3f(4)(a) shall be used for design and analysis of all seismically isolated structures, if any one of the following conditions apply:

- The structure is located on a Class E or F site; or

- The structure is located at a site with S_1 greater than 0.60g.

e. Equivalent Lateral Force Procedure.

(1) General. Except as provided in Paragraph 8-3d, every seismically isolated structure or portion thereof may be designed and constructed to resist minimum earthquake displacements and forces, as specified by this Paragraph and the applicable requirements of FEMA 302.

(2) Minimum lateral displacements.

(a) Design displacement. The isolation system shall be designed and constructed to withstand minimum lateral earthquake displacements that act in the direction of each of the main horizontal axes of the structure in accordance with the following:

$$D_D = \left(\frac{g}{4p^2}\right)\frac{S_{D1}T_D}{B_D} \qquad (8\text{-}1)$$

where:

g = acceleration of gravity. The units of the acceleration of gravity, g, are in./sec_2 (mm/sec_2) if the units of the design displacement, D_D, are inches (mm).

S_{D1} = design 5 percent damped spectral acceleration in g units at 1 sec period for Ground

Motion A or Ground Motion B, as defined in Chapter 4.

T_D = effective period, in seconds (sec), of seismically isolated structure at the design displacement in the direction under consideration, as prescribed by Equation 8-2.

B_D = numerical coefficient related to the effective damping of the isolation system at the design displacement, β_D, as set forth in Table 8-1.

(b) Effective period. The effective period of the isolated structure, T_D, shall be determined using the deformational characteristics of the isolation system in accordance with the following equation:

$$T_D = 2\pi\sqrt{\frac{W}{k_{D\min} g}} \qquad (8\text{-}2)$$

where:

W = total seismic dead load weight of the structure above the isolation interface as defined in Sections 5.3.2 and 5.5.3 of FEMA 302 (kip or kN).

$k_{D\min}$ = minimum effective stiffness, in kips/inch (kN/mm), of the isolation system at the design displacement in the horizontal direction under consideration.

g = acceleration of gravity. The units of the acceleration of gravity, g, are in./sec^2 (mm/sec^2) if the units of the design displacement, D_D, are inches (mm).

(c) Maximum displacement. The maximum displacement of the isolation system, D_M, in the most critical direction of horizontal response shall be calculated in accordance with the formula:

$$D_M = \frac{\left(\frac{g}{4\pi^2}\right) S_{M1} T_M}{B_M} \qquad (8\text{-}3)$$

where:

g = acceleration of gravity. The units of the acceleration of gravity, g, are in./sec^2 (mm/sec^2) if the units of the design displacement, D_D, are inches (mm).

S_{M1} = maximum considered 5 percent damped spectral acceleration at 1-second period as determined in Chapter 3.

T_M = effective period, in seconds, of seismic-isolated structure at the maximum displacement in the direction under consideration as prescribed by Equation 8-4.

B_M = numerical coefficient related to the effective damping of the isolation system at the maximum displacement, β_D, as set forth in Table 8-1.

(d) Effective period at maximum displacement. The effective period of the isolated structure at maximum displacement, T_M, shall be determined using the deformational characteristics of the isolation system in accordance with the equation:

$$T_M = 2\pi\sqrt{\frac{W}{k_{M\min} g}} \qquad (8\text{-}4)$$

where:

W = total seismic dead load weight of the structure above the isolation interface as defined in Sections 5.3.2 and 5.5.3 of FEMA 302.

$k_{M\min}$ = minimum effective stiffness, in kips/inch (kN/mm), of the isolation system at the maximum displacement in the horizontal direction under consideration.

g = the acceleration due to gravity. The units of the acceleration of gravity, g, are in./sec^2 (mm/sec^2) of the units of the design displacement, D_D, are inches (mm).

(e) Total displacement. The total design displacement, D_{TD}, and the total maximum displacement, D_{TM}, of elements of the isolation system shall include additional displacement due to actual and accidental torsion calculated considering the spatial distribution of the lateral stiffness of the isolation system, and the most disadvantageous location of mass eccentricity.

1. The total design displacement, D_{TD}, and the total maximum displacement, D_{TM}, of elements of an isolation system with uniform spatial distribution of lateral stiffness shall not be taken as less than that prescribed by the following equations:

$$D_{TD} = D_D\left[1 + y\left(\frac{12e}{b^2 + d^2}\right)\right] \quad (8\text{-}5)$$

$$D_{TM} = D_M\left[1 + y\left(\frac{12e}{b^2 + d^2}\right)\right] \quad (8\text{-}6)$$

where:

D_D = design displacement, in inches (mm), at the center of rigidity of the isolation system in the direction under consideration as prescribed by Equation 8-1.

D_M = maximum displacement, in inches (mm) at the center of rigidity of the isolation system in the direction under consideration as prescribed in Equation 8-3.

y = the distance, in feet (mm), between the center of rigidity of the isolation system rigidity and the element of interest measured perpendicular to the direction of seismic loading under consideration.

e = the actual eccentricity, in feet (mm), measured in plan between the center of mass of the structure above the isolation interface and the center of rigidity of the isolation system, plus accidental eccentricity, in feet (mm), taken as 5 percent of the longest plan dimension of the structure perpendicular to the direction of force under consideration.

b = the shortest plan dimension of the structure, in feet (mm), measured perpendicular to d.

d = the longest plan dimension of the structure, in feet (mm).

(3) Minimum lateral force.

(a) Isolation system structural elements at or below the isolation system. The isolation system, the foundation, and all structural elements below the isolation system shall be designed and constructed to withstand a minimum lateral seismic force, V_s, using all of the appropriate provisions for a nonisolated structure, where:

$$V_s = k_{D\max} D_D \quad (8\text{-}7)$$

where:

$k_{D\max}$ = maximum effective stiffness, in kips/inch (kN/mm), of the isolation system at the design displacement in the horizontal direction under consideration.

D_D = design displacement, in inches (mm), at the center of rigidity of the isolation system in the direction under consideration as prescribed by Equation 8-1.

In all cases, V_b shall not be taken as less than the maximum force in the isolation system at any displacement, up to and including the design displacement.

(b) Structural elements above the isolation system. The structure above the isolation system shall be designed and constructed to withstand a minimum shear force, V_s, using all of the appropriate provisions for a nonisolated structure, where:

$$V_S = \frac{k_{D\max} D_D}{R_I} \quad (8\text{-}8)$$

where:

$k_{D\max}$ = maximum effective stiffness, in kips/inch (kN/mm), of the isolation system at the design displacement in the horizontal direction under consideration.

D_D = design displacement, in inches (mm), at the center of rigidity of the isolation system in the direction under consideration as prescribed by Equation 8-1.

R_I = numerical coefficient related to the type of lateral-force-resisting system above the isolation system.

The R_I factor shall be based on the type of lateral-force-resisting system used for the structure above the isolation system and shall be 3/8 of the R value given in Table 7-1, with an upper-bound value not to exceed 2.0, and a lower-bound value not to be less than 1.0.

(4) Vertical distribution of force. The total force shall be distributed over the height of the structure above the isolation interface in accordance with the following equation:

$$F_x = \frac{V_s w_x h_x}{\sum_{i=1}^{n} w_i h_i} \quad (8\text{-}9)$$

where:

V_s = total lateral seismic design force or shear on elements above the isolation system as prescribed by Equation 8-8.

w_x = portion of w that is located at or assigned to Level x.

h_x = height above the base Level x.

w_i = portion of w that is located at or assigned to Level I, respectively.

h_i = height above the base Level I.

At each level designated as x, the force, F_x, shall be applied over the area of the structure in accordance with the mass distribution at the level. Stresses in each structural element shall be calculated as the effect of force, F_x, applied at the appropriate levels above the base.

(5) Drift limits. The maximum interstory drift of the structure above the isolation system shall not exceed $0.015h_{sx}$. The drift shall be calculated by Equation 5.3.7-1 of FEMA 302, with the C_d factor of the isolated structure equal to the R_I factor defined in Paragraph 8-3e(3)(b).

f. Dynamic Lateral Response Procedure.

(1) General. Except as required by Paragraph 8-3d, every seismically isolated structure or portion thereof may be designed and constructed to resist earthquake displacements and forces as specified in this Paragraph and the applicable requirements of Section 5.4 of FEMA 302.

(2) Isolation system and structural elements below the isolation system.

(a) The total design displacement of the isolation system shall be taken as not less than 90 percent of D_{TD} as specified by Paragraph 8-3e(2)(e). The total maximum displacement of the isolation system shall be taken as not less than 80 percent of D_{TM}, as specified by Paragraph 8-3e(2)(e). The design lateral shear force on the isolation system and structural elements below the isolation system shall be taken as not less than 90 percent of V_b as prescribed by Equation 8-7. The limits of Paragraphs 8-3e(3)(a) and (b) shall be evaluated using values of D_{TD} and D_{TM} determined in accordance with Paragraphs 8-3e(2)(a) and (c), except that D'_D is permitted to be used on lieu of D_D and D'_M is permitted to be used in lieu of D_M where D'_D and D'_M are prescribed by the following equations:

$$D'_D = \frac{D_D}{\sqrt{1+\left(\frac{T}{T_D}\right)^2}} \qquad (8\text{-}10)$$

$$D'_M = \frac{D_M}{\sqrt{1+\left(\frac{T}{T_M}\right)^2}} \qquad (8\text{-}11)$$

where:

D_D = design displacement, in inches (mm), at the center of rigidity of the isolation system in the direction under consideration as prescribed by Equation 8-1.

D_M = maximum displacement in inches (mm), at the center of rigidity of the isolation system in the direction under consideration as prescribed by Equation 8-3.

T = elastic, fixed-base period of the structure above the isolation system as determined by Section 5.3.3 of FEMA 302.

T_D = effective period, in seconds, of the seismically isolated structure at the design displacement in the direction under consideration as prescribed by Equation 8-2.

T_M = effective period, in seconds, of the seismically isolated structure at the maximum displacement in the direction under consideration as prescribed by Equation 8-4.

(3) Structural elements above the isolation system. The design lateral shear force on the structure above the isolation system, if regular in configuration, shall be taken as not less than 80 percent of V_S, as prescribed by Equation 8-8 and the limits specified by Section 13.3.4.3 of FEMA 302.

Exception: The design lateral shear force on the structure above the isolation system, if regular in configuration, is permitted to be taken as less than 80 percent, but not less than 60 percent of V_S, provided time-history analysis is used for design of the structure.

The design lateral shear force on the structure above the isolation system, if irregular in configuration, shall be taken as not less than V_S, as prescribed by Equation 8-8 and the limits specified by section 13.3.4.3 of FEMA 302.

Exception: The design lateral shear force on the structure above the isolation system, if irregular in configuration, is permitted to be taken as less than 100 percent, but not less than 80 percent of V_S, provided time-history analysis is used for design of the structure.

(4) Ground motion.

(a) Design spectra. A design spectrum shall be constructed for the design earthquake. This design spectrum shall be taken as not less than the design earthquake response spectrum given in Figure 3-2. Properly substantiated site-specific spectra are required for the design of all structures located on a Class E or F site, or located at a site with S_1 greater than 0.60g. Structures that do not require site-specific spectra and for which site–specific spectra have not been calculated shall be designed using the response spectrum shape given in Figure 3-2.

Exception: If a site-specific spectrum is calculated for the design earthquake, the design spectrum is permitted to be taken as less than 100 percent, but not less than 80 percent, of the design earthquake response spectrum given in Figure 3-2.

A design spectrum shall be constructed for the maximum considered earthquake. This design spectrum shall be taken as not less than 1.5 times the design earthquake response spectrum given in Figure 3-2. This design spectrum shall be used to determine the total maximum displacement and overturning forces for design and testing of the isolation system.

Exception: If a site-specific spectrum is calculated for the maximum considered earthquake, the design spectrum is permitted to be taken as less than 100 percent, but not less than 80 percent of 1.5

times the design earthquake response spectrum given in Figure 3-2.

(b) Time histories. Pairs of appropriate horizontal ground-motion time-history components shall be selected and scaled from not less than three recorded events. Appropriate time histories shall be based on recorded events with magnitudes, fault distances, and source mechanisms that are consistent with those that control the design earthquake (or maximum considered earthquake). Where three appropriate recorded ground-motion time-history pairs are not available, appropriate simulated ground-motion time-history pairs are permitted to be used to make up the total number required. For each pair of horizontal ground-motion components, the square root sum of the squares of the 5 percent damped spectrum of the scaled, horizontal components shall be constructed. The motions shall be scaled such that the average value of the square-root-sum-of-the squares spectra does not fall below 1.3 times the 5 percent damped spectrum of the design earthquake (or maximum considered earthquake) by more than 10 percent for periods from $0.5T_D$ seconds to 1.25 T_M seconds.

(5) Analytical procedure.

(a) General. Response-spectrum and time-history analyses shall be performed in accordance with Section 5.4 of FEMA 302, and the requirements of the following Paragraphs.

(b) Input earthquake. The design earthquake shall be used to calculate the total design displacement of the isolation system and the lateral forces and displacements of the isolated structure. The maximum considered earthquake shall be used to calculate the total maximum displacement of the isolation system.

(c) Response-spectrum analysis. Response-spectrum analysis shall be performed using a modal damping value for the fundamental mode in the direction of interest not greater than the effective damping of the isolation system or 30 percent of critical, whichever is less. Modal damping values for higher modes shall be selected consistent with those appropriate for response spectrum analysis of the structure above the isolation system with a fixed base. Response-spectrum analysis used to determine the total design displacement and the total maximum displacement shall include simultaneous excitation of the model by 100 percent of the most critical direction of ground motion, and 30 percent of the ground motion on the orthogonal axis. The maximum displacement of the isolation system shall be calculated as the vectorial sum of the two orthogonal displacements. The design shear at any story shall not be less than the story shear obtained using Equation 8-9 and a value of V_S taken as that equal to the base shear obtained from the response-spectrum analysis in the direction of interest.

(d) Time-history analysis. Time-history analysis shall be performed with at least three appropriate pairs of horizontal time-history components as defined in Paragraph 8-3f(4)(b). Each pair of time histories shall be applied simultaneously to the model considering the most disadvantageous location of mass eccentricity. The maximum displacement of the isolation system shall be calculated from the vectorial sum of the two orthogonal components at each time step. The parameter of interest shall be calculated for each time-history analysis. If three time-history analyses are performed, the maximum response of the parameter of interest shall be used for design. If seven or more time-history analyses are performed, the average value of the response parameter of interest shall be used for design.

(6) Design lateral force.

(a) Isolation system and structural elements at or below the isolation system. The isolation system, foundation, and all structural elements below the isolation system shall be designed using all of the appropriate requirements for a non-isolated structure and the forces obtained from the dynamic analysis without reduction.

(b) Structural elements above the isolation system. Structural elements above the isolation system shall be designed using the appropriate provisions for a non-isolated structure and the forces obtained from the dynamic analysis divided by a factor of R_I. The R_I factor shall be based on the type of lateral-force-resisting system used for the structure above the isolation system.

(c) Scaling of results. When the factored lateral shear force on structural elements, determined using either response-spectrum or time-history analysis, is less than the minimum level prescribed by Paragraph 8-3f(2) and 8-3f(3), all response parameters, including member forces and moments, shall be adjusted proportionally upward.

(d) Drift limits. Maximum interstory drift corresponding to the design lateral force, including displacement due to vertical deformation of the isolation system, shall not exceed the following limits:

1. The maximum interstory drift of the structure above the isolation system calculated by response-spectrum analysis shall not exceed $0.015h_{sx}$, and

2. The maximum interstory drift of the structure above the isolation system calculated by time-history analysis considering the force-deflection characteristics of nonlinear elements of the lateral-force-resisting system shall not exceed $0.020h_{sx}$.

Drift shall be calculated using Equation 5.3.8.1 of FEMA 302 with the C_d factor of the isolated structure equal to the R_I factor defined in Paragraph 8-3e(3)(b). The secondary effects of the maximum considered earthquake lateral displacement) of the structure above the isolation system combined with gravity forces shall be investigated if the interstory drift ratio exceeds $0.010/R_I$.

g. Acceptance Criteria.

(1) Performance Objective 1A. Compliance with the provisions of Paragraphs 8-3e or 8-3f with Ground Motion as the design ground motion will be considered to satisfy this performance objective.

(2) Enhanced performance objectives. The design ground motion for enhanced performance objectives will be as indicated in Table 4-4. The analysis will be performed without the response modification factor, R_I, and the acceptance criteria

will be as prescribed in Chapter 6 with the appropriate *m* values from Chapter 7.

h. Lateral Load on Nonstructural Systems and Components Supported by Buildings.

(1) General. Parts or portions of an isolated structure, permanent nonstructural components and the attachments to them, and the attachments for permanent equipment supported by a structure shall be designed to resist seismic forces and displacements as prescribed by this section and the applicable requirements of Chapter 10. Buildings with isolation systems should use rigid horizontal diaphragms or bracing systems above and below the isolator level to provide deformation compatibility among the resisting structural elements. When the isolation system is located immediately above the building foundations, a reinforced concrete slab or a system of tie beams should be provided for displacement compatibility among the footings or pile caps.

(2) Forces and displacements.

(a) Components at or above the isolation interface. Elements of seismically isolated structures and nonstructural components, or portions thereof , that are at or above the isolation interface shall be designed to resist a total lateral seismic force equal to the maximum dynamic response of the element or component under consideration.

Exception: Elements of seismically isolated structures and nonstructural components or portions thereof are permitted to be designed to resist total lateral seismic force as prescribed by Equation 5.2.6-1 or 5.2.6-2 of FEMA 302, as appropriate.

(b) Components crossing the isolation interface. Elements of seismically isolated structures and nonstructural components, or portions thereof, that cross the isolation interface, shall be designed to withstand the total maximum displacement.

(c) Components below the isolation interface. Elements of seismically isolated structures and nonstructural components, or portions thereof, that are below the isolation interface shall be designed and constructed in accordance with the requirements of Section 5.2 of FEMA 302.

i. Detailed System Requirements. The isolation system and the structural system shall comply with the material requirements of FEMA 302. In addition, the isolation system shall comply with the detailed system requirements of this chapter, and the structural system shall comply with the requirements of this document and the applicable portions of Section 5.2 of FEMA 302.

j. Design and Construction Review.

(1) General. A design review of the isolation system and related test programs shall be performed by an independent peer review team of registered design professionals in the appropriate disciplines, and others experienced in seismic analysis methods and the theory and application of seismic isolation.

(2) Isolation system. Isolation system design review shall include, but not be limited to, the following:

(a) Review of site-specific seismic criteria, including the development of site-specific spectra and ground motion time histories and all other design criteria developed specifically for the project;

(b) Review of the preliminary design, including the determination of the total design displacement of the isolation system design displacement and the lateral force design level;

(c) Overview and observation of prototype testing, Paragraph 8-3k;

(d) Review of the final design of the entire structural system and all supporting analyses; and

(e) Review of the isolation system quality control testing program, Paragraph 8-3i(2)(i).

k. Required Tests of the Isolation System. Required testing to establish and validate the design perspectives of the isolation system shall be in accordance with the requirements of Section 13.9 of FEMA 302.

8-4. Energy Dissipation Systems.

a. Design Concept. These systems are designed to provide supplemental damping in order to reduce the seismic input forces. Most conventional buildings are designed assuming 5 percent equivalent viscous damping for structures responding in the elastic range. For structures that include viscous dampers or metallic yielding devices, the equivalent viscous damping may be increased to between 15 percent and 25 percent, depending on the specific characteristics of the device. In this way, seismic input energy to the structure is largely dissipated through the inelastic deformations concentrated in the devices, reducing damage to other critical elements of the building. The benefits resulting from the use of displacement-dependent energy dissipation devices are attributed primarily to the reduction in spectral demand due to supplemental damping provided by the devices. A preliminary evaluation of these benefits requires the following considerations:

(1) From a linear elastic static or modal analysis of the building, determine the story displacements without the energy dissipation devices.

(2) Select target design displacement, D_{Di}, at each story. From test data furnished by the manufacturer, determine the effective stiffness, K_{eff}, of the proposed devices at each story using Equation 8-13.

(3) Based on the effective stiffness of the devices and the assumed target displacements, calculate the effective damping, $, in accordance with Equations 8-18 and 8-19.

(4) Modify the design response spectrum to represent the effective damping using Table 8-2 and Figure 8-8.

(5) Modify the mathematical model of the building to incorporate the effective stiffness of the devices in each story.

Effective Damping ß (percent of critical)[1]	**B_S**	**B_1**
<2	0.8	0.8
5	1.0	1.0
10	1.3	1.2
20	1.8	1.5
30	2.3	1.7
40	2.7	1.9
>50	3.0	2.0

[1] The damping coefficient should be based on linear interpolation for effective damping values other than those given.

Table 8-2 Damping Coefficients B_s and B_1 as a Function of Effective Damping b

(6) Perform the analysis of the revised model with the modified spectrum and compare the story displacements with the assumed target displacements. If necessary, revise the target displacements and reiterate the analysis.

(7) Optimize the design by using several assumed values of the effective stiffness of the devices and the target displacements.

Evaluation of the benefits of velocity-displacement energy-dissipation devices is much more complex and beyond the scope of this document. Guidance for such an evaluation can be obtained from the design examples in FEMA 274 (Commentary to FEMA 273).

b. Device Description. A number of energy-dissipation devices are currently in use or proposed for use in the U.S. The specific properties vary widely. Some of these systems use viscous fluids or viscoelastic materials; some rely on the hysteretic behavior of metallic elements; and others use sliding systems that rely on frictional resistance. The systems that use viscous and viscoelastic materials are rate-dependent (i.e., the hysteretic response of the device depends upon the rate of loading), and also may be temperature sensitive. The other systems are generally rate-independent.

c. Applications. Supplemental damping may significantly reduce the seismic input where the structural period is in resonance with the predominant period of the site. If the structural period and site period are widely separated, added damping may have only a marginal effect on the response. It should be noted that the reduction of the response is most dramatic when the frequency of the structural system (including the effects of the yielding device) coincides with the frequency at the peak of the input acceleration spectrum. This is shown in Figures 8-5 and 8-6 using four representative building types and two different soil types, represented by earthquake response spectra. These examples are constructed to demonstrate the effect of the supplemental damping. For the sake of simplicity, the effect of the added stiffness has been included with the building period cited below.

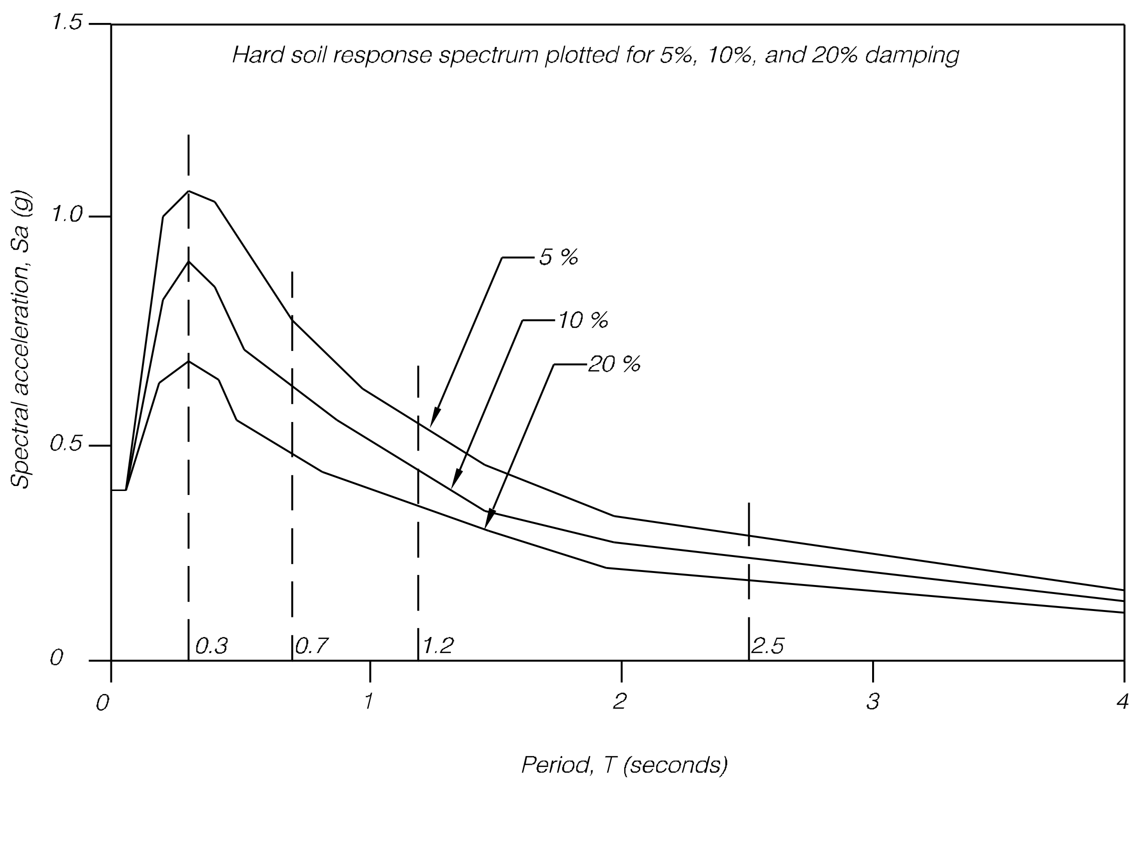


Figure 8-5 Supplemental damping hard soil example

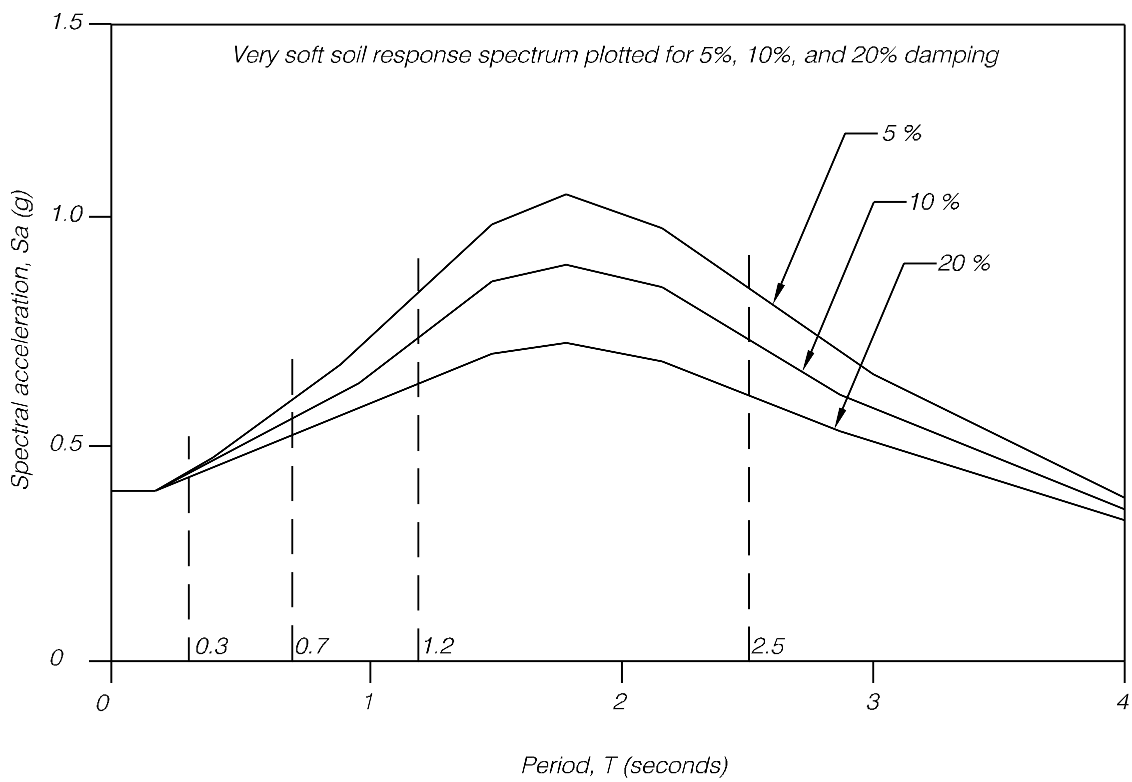


Figure 8-6 Supplemental damping very soft soil example

- Concrete shear wall or steel braced frame building; *T* = 0.3 seconds;

- Concrete frame building; *T* = 0.7 seconds;

- Steel frame building; *T* = 1.2 seconds;

- Tall steel frame; *T* = 2.5 seconds.

d. Design Criteria.

(1) General.

(a) The energy-dissipation devices should be designed with consideration given to other environmental conditions, including wind, aging effects, creep, fatigue, ambient temperature, operating temperature, and exposure to moisture or damaging substances.

(b) The building height limitations should not exceed the limitations for the structural system into which the energy-dissipation devices are implemented.

(c) The mathematical model of a building should include the plan and vertical distribution of the energy-dissipation devices. Analysis of the mathematical model should account for the dependence of the devices on excitation frequency, ambient and operating temperature, velocity, sustained loads, and bilateral loads. Multiple analyses of the building may be necessary to capture the effects of varying mechanical characteristics of the devices.

(d) Energy-dissipation devices shall be capable of sustaining larger displacements (and velocities for velocity-dependant devices) than the maximum calculated in the MCE. The increase in displacement (and velocity) capacity is dependent on the level of redundancy in the supplemental damping system as follows:

1. If four or more energy dissipation devices are provided in a given story of a building, in one principal direction of the building, with a minimum of two devices located on each side of the center of stiffness of the story in the direction under consideration, all energy dissipation devices shall be capable of sustaining displacements equal to 130 percent of the maximum calculated displacement in the device in the MCE. A velocity-dependant device shall also be capable of sustaining the force associated with a velocity equal to 130 percent of the maximum calculated velocity for that device in the MCE.

2. If fewer than four energy dissipation devices are provided in a given story of a building, in one principal direction of the building, or fewer than two devices are located on each side of the center of stiffness of the story in the direction under consideration, all energy-dissipation devices shall be capable of sustaining displacements equal to 200 percent of the maximum calculated displacement in the device in the MCE. A velocity-dependant device shall also be capable of sustaining the force associated with a velocity equal to 200 percent of the maximum calculated velocity for that device in the MCE.

(e) The components and connections transferring forces between the energy dissipation devices shall be designed to remain linearly elastic for the forces described in items (d)1 or (d)2 above, depending upon the degree of redundancy in the supplemental damping system.

(2) Modeling of energy-dissipation devices.

(a) Energy-dissipation devices are classified as either displacement-dependent, velocity-dependent, or other. Displacement-dependent devices may exhibit either rigid-plastic (friction devices), bilinear (metallic yielding devices), or trilinear hysteresis. The response of displacement-dependent devices should be independent of velocity and/or frequency of excitation. Velocity-dependent devices include solid and fluid viscoelastic devices, and fluid viscous devices. The third classification (other) includes all devices that cannot be classified as either displacement- or velocity-dependent. Examples of "other" devices include shape memory alloys (superelastic effect), friction-spring assemblies with recentering capability, and fluid-restoring force-damping devices.

(b) Models of the energy dissipation system should include the stiffness of structural components that are part of the load path between the energy-dissipation devices and the ground, if the flexibility of these components is significant enough to affect the performance of the energy dissipation system. Structural components whose flexibility could affect the performance of the energy dissipation system include components of the foundation, braces that work in series with the energy dissipation devices, and connections between braces and the energy dissipation devices.

(c) Energy dissipation devices should be modeled as described in the following subsection, unless more advanced methods or phenomenological models are used.

(3) Displacement-dependent devices.

(a) The force-displacement response of a displacement-dependent device is primarily a function of the relative displacement between each end of the device. The response of such a device is substantially independent of the relative velocity between each end of the device, and/or frequency of excitation.

(b) Displacement-dependent devices should be modeled in sufficient detail so as to capture their force-displacement response adequately, and their dependence, if any, on axial-shear-flexure interaction, or bilateral deformation response.

(c) For the purposes of evaluating the response of a displacement-dependent device from testing data, the force in a displacement-dependent device may be expressed as:

$$F = k_{\text{eff}} D \tag{8-12}$$

where the effective stiffness k_{eff} of the device is calculated as:

$$k_{\text{eff}} = \frac{|F^+| + |F^-|}{|D^+| + |D^-|} \tag{8-13}$$

and where forces in the device, F^+ and F^-, are evaluated at displacements D^+ and D^-, respectively.

(4) Velocity-dependent devices.

The force-displacement response of a velocity-dependent device is primarily a function of the relative velocity between each end of the device.

(a) Solid viscoelastic devices. The cyclic response of viseoelastic solids is generally dependent on the frequency and amplitude of the motion, and the operation temperature (including temperature rise due to excitation).

1. Solid viseoelastic devices may be modeled using a spring and dashpot in parallel (Kelvin model). The spring and dashpot constants selected should adequately capture the frequency and temperature dependence on the device consistent with fundamental frequency of the building (f_1), and the operating temperature range. If the cyclic response of a viseoelastic solid device cannot be adequately captured by single estimates of the spring and dashpot constants, the response of the building should be estimated by multiple analyses of the building frame, using limited values for the spring and dashpot constants.

2. The force in a viseoelastic device may be expressed as:

$$F = k_{\text{eff}} D + C \dot{D} \qquad (8\text{-}14)$$

where C is the damping coefficient for the viscoelastic device, D is the relative displacement between each end of the device, $\dot{D}$ is the relative velocity between each end of the device, and k_{eff} is the effective stiffness of the device calculated as:

$$k_{\text{eff}} = \frac{|F^+| + |F^-|}{|D^+| + |D^-|} = K^1 \qquad (8\text{-}15)$$

where K^1 is the so-called storage stiffness.

3. The damping coefficient for the device shall be calculated as:

$$C = \frac{W_D}{p w_1 D_{\text{ave}}^2} = \frac{K^{11}}{w_1} \qquad (8\text{-}16)$$

where K^{11} is the loss stiffness, the angular frequency T_1 is equal to $2Bf_1$, D_{ave} is the average of the absolute values of displacements D^+ and D^-, and W_D is the area enclosed by one complete cycle of the force-displacement response of the device.

(b) Fluid viscoelastic devices. The cyclic response of viscoelastic fluid devices is generally dependent on the frequency and amplitude of the motion, and the operation temperature (including temperature rise due to excitation). Fluid viscoelastic devices may be modeled using a spring and dashpot in series (Maxwell model). The spring and dashpot constants selected should adequately capture the frequency and temperature dependence of the device consistent with fundamental frequency of the rehabilitated building (f_1), and the operation temperature range. If the cyclic response of a viscoelastic fluid device cannot be adequately captured by single estimate of the spring and dashpot constants, the response of the building should be estimated by multiple analyses of the building frame, using limiting values for the spring and dashpot constants.

(c) Fluid viscous devices.

1. The cyclic response of a fluid viscous device is dependent on the velocity of motion; may be dependent on the frequency and amplitude of the motion; and is generally dependent on the operation temperature (including temperature rise due to excitation). Fluid viscous devices may exhibit some stiffness at high frequencies of cyclic loading. Linear fluid viscous dampers exhibiting stiffness in the frequency range 0.5 f_1 to 2.0 f_1 should be modeled as a fluid viscoelastic device.

2. In the absence of stiffness in the frequency range 0.5 f_1 to 2.0 f_1, the force in the fluid viscous device may be expressed as:

$$F = C_O \left|\dot{D}\right|^{a} sgn\left(\dot{D}\right) \qquad (8\text{-}17)$$

where C_0 is the damping coefficient for the device, ″ is the velocity exponent for the device, $\dot{D}$ is the relative velocity between each end of the device, and *sgn* is the signum function that, in this case, defines the sign of the relative velocity term.

(d) Other types of devices. Energy dissipation devices not classified as either displacement-dependent or velocity-dependent should be modeled using either established principles of mechanics or phenomenological models. Such models should accurately describe the force-velocity-displacement response of the device under all sources of loading (e.g., gravity, seismic, thermal).

e. Linear Analytical Procedures.

(1) General.

(a) Linear procedures are only permitted if it can be demonstrated that the framing system exclusive of the energy dissipation devices remains essentially linearly elastic for the level of earthquake demand of interest after the effects of added damping are considered. Further, the effective damping afforded by the energy dissipation shall not exceed 30 percent of critical in the fundamental mode. Other limits on the use of linear procedures are presented below.

(b) The secant stiffness, K_s, of each energy dissipation device, calculated at the maximum displacement in the device, in a manner similar to that indicated in Figure 8-7 for the target displacement of the building, shall be included in the mathematical model of the rehabilitated building. For the purpose of evaluating the regularity of a building, the energy dissipation devices shall be included in the mathematical mode.

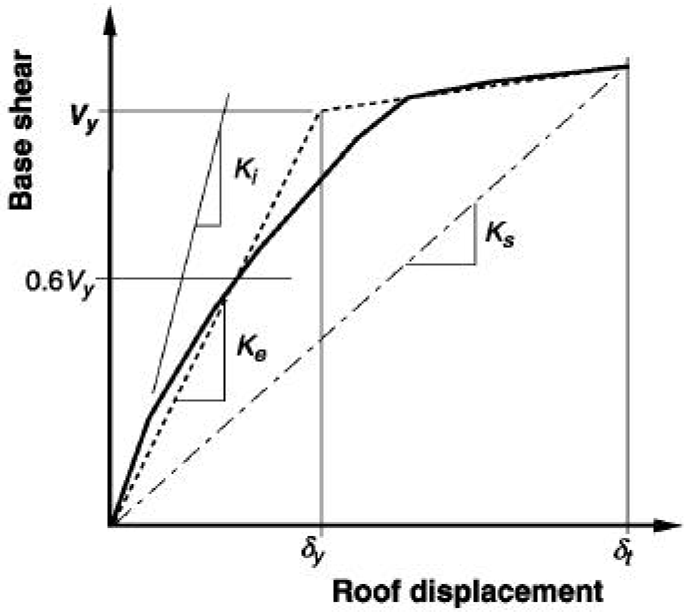


Figure 8-7 Calculation of Secant Stiffness, K_S

(2) Linear Static Procedures.

(a) Displacement-dependent device. The Linear Static Procedure (LSP) may be used to implement displacement-dependent energy dissipation devices, provided that the following requirements are satisfied:

1. The ratio of the maximum resistance in each story, in the direction under consideration, to the story shear demand calculated using Equations 5.3.4-1 and 5.3.4-2 in FEMA 302, shall range between 80 percent and 120 percent of the average value of the ratio for all stories. The maximum story resistance shall include the contributions from all components, elements, and energy-dissipation devices.

2. The maximum resistance of all energy-dissipation devices in a story, in the direction under consideration, shall not exceed 50 percent of the resistance of the remainder of the framing, where said resistance is calculated at the displacements anticipated in the MCE. Aging and environmental effects shall be considered in calculating the maximum resistance of the energy dissipation devices.

3. The base shear and story forces calculated by Equations 5.3.4-1 and 5.3.4-2 in FEMA should be reduced by the damping modification factors in Table 8-2 to account for the energy dissipation (damping) affected by the energy dissipation devices. Figure 8-8 indicates how the response spectrum is modified by the damping coefficient B_s and B_1 in Table 8-2. In Figure 8-8, the spectral ordinates S_{xs} and S_{x1} represent the 0.2 second and the 1.0 second ordinates for Ground Motion A or B, or for the MCE. The calculation of the effective damping is estimated as follows:

$$b_{\text{eff}} = b + \frac{\sum_{\text{i}} W_j}{4pW_k} \qquad (8\text{-}18)$$

where $\$$ is the damping in the framing system, and is set equal to 0.05, unless modified. W_j is work done by device j in one complete cycle corresponding to floor displacements $*_i$, the summation extends over all devices j, and W_k is the maximum strain energy in the frame, determined using Equation 8-19.

$$W_k = \frac{1}{2}\sum_i F_i d_i \qquad (8\text{-}19)$$

where F_{I} is the inertia force at floor level I, and the summation extends over all floor levels.

(b) Velocity-dependent devices.

1. The LSP may be used to implement velocity-dependent energy-dissipation devices, provided that the following requirement is satisfied:

- The maximum resistance of all energy-dissipation devices in a story, in the direction under consideration, shall not exceed 50 percent of the resistance of the remainder of the framing, where said resistance is calculated at the displacements anticipated in the MCE. Aging and environmental effects shall be considered in calculating the

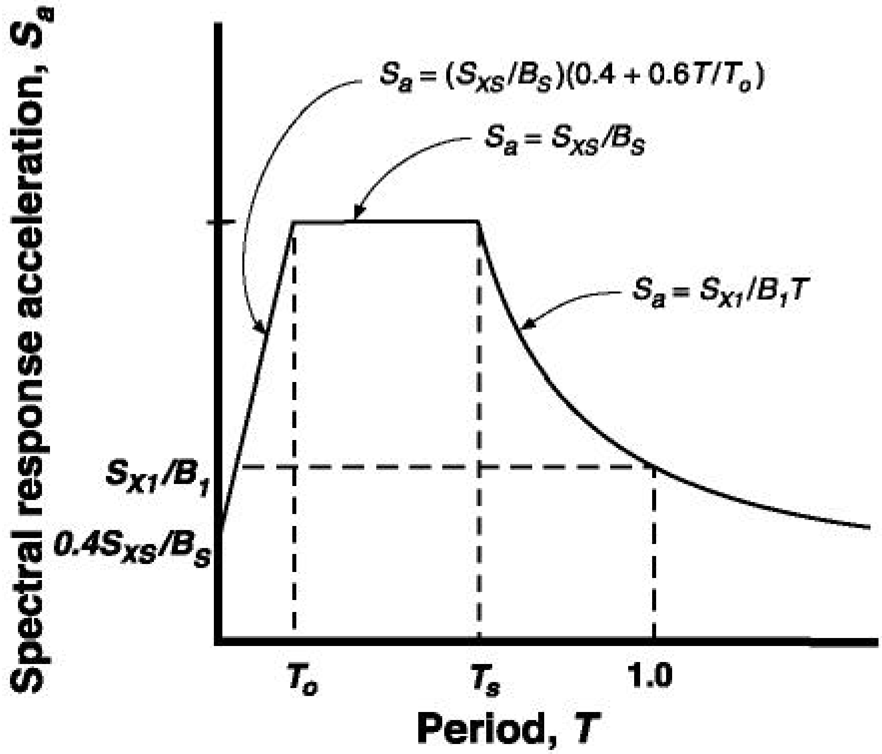


Figure 8-8   General Response Spectrum

maximum resistance of the energy-dissipation devices.

2. The base shear and story forces should be reduced, as described above, by the damping modification factors in Table 8-2 to account for the energy dissipation (damping) afforded by the energy-dissipation devices. The calculation for effective damping is estimated as:

$$\beta_{\text{eff}} = \beta + \frac{\sum_i W_j}{4\pi W_k} \qquad (8\text{-}20)$$

where β is the damping in the structural frame, and is set equal to 0.05 unless modified in Section 2.6.1.5, W_j is work done by device j in one complete cycle corresponding to floor displacements δ_i, the summation extends over all devices j, and W_k is the maximum strain energy in the frame, determined using Equation 8-19.

3. The work done by linear viscous device j in one complete cycle of loading may be calculated as:

$$W_j = \frac{2\pi^2}{T} C_j \delta_{rj}^2 \qquad (8\text{-}21)$$

where T is the fundamental period of the building, including the stiffness of the velocity-dependent devices, C_j is the damping constant for device j, and δ_{rj} is the relative displacement between the ends of device j along the axis of device j. An alternative equation for calculating the effective damping of Equation 8-20 is:

$$\beta_{eff} = \beta + \frac{T \sum_i C_j \cos^2\theta_j \phi_{rj}^2}{\pi \sum_i \left(\frac{w_i}{g}\right) \phi_i^2} \qquad (8\text{-}22)$$

where θ_j is the angle of inclination of device j to the horizontal, ϕ_{rj} is the first mode relative displacement between the ends of device j in the horizontal direction, w_i is the reactive weight of floor level i, ϕ_i is the first mode displacement at floor level i, and other terms are as defined above. Equation 8-22 applies to linear viscous devices only.

4. The design actions for components of the building should be calculated in three distinct stages of deformation, as follows. The maximum action should be used for design.

i. At the stage of maximum drift. The lateral forces at each level of the building should be calculated using Equations 5.3.4-1 and 5.3.4-2 in FEMA 302, where V is the modified equivalent base shear.

ii. At the stage of maximum velocity and zero drift. The viscous component of force in each energy dissipation device should be calculated by Equations 8-14 or 8-17, where the relative velocity $\dot{D}$ is given by $2\pi f_1 D$, where D is the relative displacement between the ends of the device calculated at the stage of maximum drift. The calculated viscous forces should be applied to the mathematical model of the building at the points of attachment of the device, and in directions consistent with the deformed shape of the building at maximum drift. The horizontal inertial forces at each floor level of the building should be applied concurrently with the viscous forces so that the horizontal displacement of each floor level is zero.

iii. At the stage of maximum floor acceleration. Design actions in components of the rehabilitated building should be determined as the sum of [actions determined at the stage of maximum drift] times [CF_1] and [actions determined at the stage of maximum velocity] times [CF_2], where

$$CF_1 = \cos\left[\tan^{-1}\left(2\beta_{eff}\right)\right] \quad (8\text{-}23)$$

$$CF_2 = \sin\left[\tan^{-1}\left(2\beta_{eff}\right)\right] \quad (8\text{-}24)$$

in which β_{eff} is defined by either Equation 8-20 or Equation 8-22.

(3) Linear Dynamic Procedure (LDP). The modal analyses procedure, described in Paragraph 3-2(c)(2), may be used when the effective damping in the fundamental mode of the building, in each principal direction, does not exceed 30 percent of critical.

(a) Displacement-dependent devices. Application of the LDP for the analysis of buildings incorporating displacement-dependent devices is subject to the restrictions set forth in Paragraph 8-4-e(2)(a).

1. For analysis by the Response Spectrum Method, the 5 percent damped response spectrum may be modified to account for the damping afforded the displacement-dependent energy-dissipation devices. The 5 percent damped acceleration spectrum should be reduced by the modal-dependent damping modification factor, *B*, and either B_s or B_l, for periods in the vicinity of the mode under consideration; note that the value of B will be different for each mode of vibration. The damping modification factor in each significant mode should be determined using Table 8-2 and the calculated effective damping in that mode. The effective damping should be determined using a procedure similar to the described in Paragraph 8-4e(2)(a).

2. If the maximum base shear force calculated by dynamic analysis is less than 80 percent of the modified equivalent base shear of Paragraph 8-4e(2)(a), component and element actions and deformations shall be proportionally increased to correspond to 80 percent of the modified equivalent base shear.

(b) Velocity-dependent devices.

1. For analysis by the Response Spectrum Method, the 5 percent damped response spectrum may be modified to account for the damping afforded by the velocity-dependent energy dissipation devices. The 5 percent damped acceleration spectrum should be reduced by the modal-dependent damping modification factor, *B*, either B_s or B_l, for periods in the vicinity of the mode under consideration; note that the value of *B* will be different for each mode of vibration. The damping modification factor in each significant mode should be determined using Table 8-2 and the calculated effective damping mode.

2. The effective damping in the *m*-th mode of vibration ($\beta_{eff\text{-}m}$) shall be calculated as:

$$\beta_{eff\text{-}m} = \beta_m + \frac{\sum_i W_{mj}}{4\pi W_{mk}} \qquad (8\text{-}25)$$

where β_m is the *m*-th mode damping in the building frame, W_{mj} is work done by device *j* in one complete cycle corresponding to modal floor displacements δ_{mi}, and W_{mk} is the maximum strain energy in the frame in the *m*-th mode, determined using Equation 8-26.

$$W_{mk} = \frac{1}{2}\sum_i F_{mi} d_{mi} \qquad (8\text{-}26)$$

where F_{mi} is the *m*-th mode horizontal inertia force at floor level *i* and δ_{mi} is the *m*-th mode horizontal displacement at floor level *i*. The work done by linear viscous device *j* in one complete cycle of loading in the *m*-th mode may be calculated as:

$$W_{mj} = \frac{2\pi^2}{T_m} C_j d_{mrj}^2 \qquad (8\text{-}27)$$

where T_m is the *m*-th mode period of the rehabilitated building, including the stiffness of the velocity-dependent devices, C_j is the damping constant for device *j*, and δ_{mrj} is the *m*-th mode relative displacement between the ends of device *j* along the axis of device *j*.

3. Direct application of the Response Spectrum Method will result in member actions at maximum drift. Member actions at maximum velocity and maximum acceleration in each significant mode should be determined using the procedure described in Paragraph 8-4e(2)(b). The combination factors CF_1 and CF_2 should be determined from Equations 8-23 and 8-24 using $\beta_{eff\text{-}m}$ for the *m*-th mode.

4. If the maximum base shear force calculated by dynamic analysis is less than 80 percent of the modified equivalent base shear of Paragraph 8-4e(3), component and element actions and deformations shall be proportionally increased to correspond to 80 percent of the modified equivalent base shear.

f. Nonlinear Elastic Static Procedure.

The nonlinear static procedure, described in Paragraph 5-4, should be followed unless explicitly modified by the following paragraphs.

(1) The nonlinear mathematical model of the building should explicitly include the nonlinear force-velocity-displacement characteristics of the energy-dissipation devices, and the mechanical characteristics of the components supporting the devices. Stiffness characteristics should be consistent with the deformations corresponding to the target displacement and frequency equal to the inverse of period T_e, as defined in Paragraph 5-4(e)(4).

(2) The nonlinear mathematical model of the building shall include the nonlinear force-velocity-displacement characteristics of the energy-dissipation devices, and the mechanical characteristic components supporting the devices. Energy-dissipation devices with stiffness and damping characteristics that are dependent on excitation frequency and/or temperature shall be modeled with characteristics consistent with (1) the deformations

expected at the target displacement, and (2) a frequency equal to the inverse of the effective period.

(3) Equation 5-5 should be used to calculate the target displacement. For velocity-dependent energy-dissipation devices, the spectral acceleration in Equation 5-5 should be reduced to account for the damping afforded by the viscous dampers.

(a) Displacement-dependent devices. Equations 5-5 should be used to calculate the target displacement. The stiffness characteristics of the energy dissipation devices should be included in the mathematical model.

(b) Velocity-dependent devices. The target displacement of Equation 5-5 should be reduced to account for the damping added by the velocity-dependent energy-dissipation devices. The calculation of the damping effect is estimated as:

$$b_{\text{eff}} = b + \frac{\sum_i W_j}{4pW_k} \qquad (8\text{-}28)$$

where $ is the damping in the structural frame and is set equal to 0.05, W_j, is work done by device in j in one complete cycle corresponding to floor displacements $*_i$, the summation extends over all devices j, and W_k is the maximum strain energy in the frame, determined using Equation 8-19. The work done by device j in one complete cycle of loading may be calculated as:

$$W_j = \frac{2p^2}{T_s} C_j d_j^2 \qquad (8\text{-}29)$$

where T_s is the secant fundamental period of the building, including the stiffness of the velocity-dependent devices (if any), calculated using Equation 5-3, but replacing the effective stiffness (K_e) with the secant stiffness (K_s) at the target displacement (see Figure 8-7); C_j is the damping constant for device j; and $*_{rj}$ is the relative displacement between the ends of device j along the axis of device j at a roof displacement corresponding to the target displacement.

g. Acceptance Criteria. The acceptance criteria for all performance objectives, prescribed in Chapter 6, and provided for building systems and components in Chapter 5, apply to buildings incorporating energy dissipation devices. The benefits of energy dissipation are realized by the reduced demand response spectrum using the damping coefficients in Table 8-2. Checking for force-controlled actions should use the component actions calculated for three limit states: maximum drift, maximum velocity, and maximum acceleration. In the nonlinear elastic static procedure, displacement-controlled actions must be checked for deformations corresponding to the target displacement. Maximum actions are to be used for design, temperature, and exposure to moisture and damaging substances.

h. Design and Construction Reviews. Design and construction review will be performed on all buildings incorporating energy-dissipation devices. The type and scope of the review will be in accordance with the requirements of Paragraph 1-9, unless modified by the requirements of this chapter. Design review of the energy-dissipation system and related test programs should be performed by an independent engineering peer review panel, including persons licensed in the appropriate disciplines, and experience in seismic analysis, including the theory and application of energy-dissipation methods. The design review should include, but should not necessarily be limited to, the following:

- Preliminary design including sizing of the devices;

- Prototype testing;

- Final design of the rehabilitated building and supporting analyses; and

- Manufacturing quality control program for the energy-dissipation devices.

i. Required Tests of Energy Dissipation Devices. Required testing, and peer review of the testing, to establish and validate the design properties of the energy-dissipation devices, shall be similar to that required by Section 13.9 and the appendix to Chapter 13 of FEMA 302.

8-5. Guidance for Selection and Use of Seismic Isolation and Energy Dissipation Systems.

a. Earthquake Damage Mitigation. Earthquake damage to nearly any structure could be reduced through the judicious use of some type of seismic isolation or energy-dissipation system. Although the initial design and construction costs for these systems may be higher than for conventional design, current data suggest that they will pay for themselves over the life of a structure in reduced earthquake damage. These systems might be appropriate for critical facilities where severe damage is unacceptable, and also for noncritical facilities where a long-term user is willing to accept the higher initial coats in exchange for reduced future damage costs.

(1) Conventional design using elastic design. Using conventional design, earthquake damage can generally be prevented only by designing for higher and higher seismic forces. Critical facilities built using conventional design may need to be designed to remain elastic even for major earthquakes. The resulting design forces must be resisted elastically by all of the critical structural and nonstructural building components. Such design procedures result in larger structural members and more costly construction than life-safety design procedures, and are rarely used except for facilities such as nuclear power plants.

(2) Seismic isolation and energy dissipation. Facilities that incorporate seismic isolation and energy dissipation systems can be designed to take advantage of the dynamic characteristics and the nonlinearities inherent in these systems to reduce the seismic accelerations and displacements. Thus, critical structural and nonstructural components may generally be designed using substantially lower element forces than would be required using elastic design procedures to achieve the same level of earthquake protection.

b. Type of Facility. Important, essential, and historic facilities may be good candidates for seismic isolation or energy-dissipation systems, since earthquake damage to such facilities may have costly and unacceptable consequences. Examples of such consequences might include a major hazardous materials release from a facility located in an urban area, major equipment malfunction at a regional emergency response center, or the destruction of an irreplaceable historic structure. Such events are unacceptable, particularly when techniques are available to prevent them. Seismic isolation or energy dissipation systems can be incorporated into the design of critical facilities to prevent these types of disasters from occurring.

c. Earthquake Effects - *Acceleration vs. Displacement.* Building components may be damaged by both seismic accelerations and seismic displacements. A particular type of component, either structural or nonstructural, may be more sensitive to one or other type of damage. In order to reduce earthquake damage, it is important to consider whether critical building components are vulnerable to acceleration damage, displacement damage, or both.

(1) Damage caused by seismic accelerations. Seismic accelerations cause intense shaking that may damage structural components, nonstructural components, and piping or sensitive equipment. A building component may be damaged when the seismic inertial forces generated within the component exceed the elastic capacity of the component to resist those forces. Some examples of damage due to excessive inertial forces caused by seismic accelerations include the following: shear cracking in a masonry shear wall; out-of-plane failure of a freestanding wall or heavy partition; shear failure of anchor bolts at the base of a piece of heavy equipment; and pipe rupture at an anchor point for a long, unbraced section of heavy pipe.

(2) Damage caused by seismic displacements. Seismic displacements may also damage building components. Nonstructural components attached to adjacent floors in multistory buildings are particularly vulnerable to displacement damage. Light items that are unlikely to generate large inertial forces may still be damaged by large imposed deformations. Nonstructural components such as glazing, precast cladding, rigid full-height partitions, sprinkler piping, hazardous material piping, and exterior veneer or ornamentation may be damaged by large interstory drifts caused by the seismic displacements of the building frame. Items that cross seismic joints between adjacent buildings are also vulnerable to displacement damage.

(3) Damage identification. It is important to identity what critical building components are vulnerable to damage, what type of damage they are vulnerable to, and what level of damage protection is desired for critical components of a given facility in order to identity effective damage reduction techniques. In some cases, acceleration control may be required in order to reduce potential acceleration damage. In other cases, displacement control may be most important. In still other cases, both acceleration and displacement control may he required to provide effective damage reduction.

d. System Selection - conventional design, seismic isolation, or energy dissipation. The selection of a structural system for a critical facility is a complex process that must take many factors into consideration. These factors include the dynamic characteristics of the building, the surrounding soil, and the critical nonstructural components. Both present construction costs and future damage costs should be considered. Proximity to an active fault may be another important consideration. Seismic isolation and energy-dissipation systems can both be effectively used to reduce earthquake damage when compared with conventional construction, but each type of system is most effective for a different range of dynamic characteristics. In addition, the selection of one or other system may depend on whether acceleration control, displacement control, or both, are required to reduce the earthquake damage at a particular facility.

(1) System comparison. Table 8-3 provides a comparison of building behavior for these three systems – conventional design, seismic isolation, and energy dissipation. Generally, seismic isolation systems are most effective in reducing damage to buildings that are already very flexible. Base isolation is most effective when the original building period is significantly shorter than the isolated building period, typically about 2.5 seconds. Energy dissipation systems are almost the reverse. They are most effective in reducing damage to flexible structures, and much less effective in reducing damage to rigid structures.

(2) Site selection - inappropriate sites. Particular care must be used in selecting a structural system for a building site located very close to an active fault or in an unmapped area that may be underlain by blind thrust faults. Recent seismic recording from near-fault sites include measurements of very large spectral displacements at some stations, and very large, one-cycle, energy pulses at other stations. Typical seismic isolation and energy dissipation systems are currently not designed to accommodate these extreme near-fault motions. In addition, seismic isolation systems are currently not designed for use at locations where the site period is in the range of 2 to 3 seconds, since this is also the range of most current isolators.

(a) Sites where seismic isolation systems are not recommended. During recent earthquakes, near-fault spectral displacements of approximately 40 inches have been measured for periods in the range of 2 to 3 seconds. Current isolators typically have periods of approximately 2.5 seconds. These isolators have not been designed to accommodate such large spectral displacements, and may fail and develop vertical instabilities. Deep soil sites with 2- to 3- second periods also would not be appropriate for seismic isolation. At such sites, the isolators could be in resonance with the ground motion, resulting in the undesired amplification of the structural response. In the future, isolation systems may he developed for these sites, but current seismic isolation techniques and hardware are not recommended for either the near-fault site, or the deep soil site with a 2- to 3- second period.

(b) Sites where energy dissipation systems are not recommended. During recent earthquakes, including both Northridge, California and Kobe, Japan, very large energy pulses have been recorded within the first few earthquake cycles at some near-fault sites. Very close to a fault, the majority of the total input energy at the site may be contained in an initial large pulse. Currently available energy dissipators are generally designed to dissipate a portion of the energy input during each of several cycles in order to obtain the maximum benefit. Current dissipators are not designed to dissipate the total input energy from a major earthquake in one or two cycles. In the future, special devices may be developed for this type of motion, but current energy-dissipation systems are not recommended for use at near-fault sites.

Table 8-3

Comparison of Building Behavior

Building Type	Conventional Design		Building with Seismic Isolation System		Building with Energy Dissipation System		Recommended System to Reduce Earthquake Damage
	Seismic Displ.	Seismic Accel.	Seismic Displ.	Seismic Accel.	Seismic Displ.	Seismic Accel.	
Rigid Buildings (shear wall, masonry construction	small	large	small	small	small	large	Seismic Isolation
Semi-rigid or semi-flexible Buildings (braced frames, stiff moment frames, tall shear walls)	moderate	moderate	small	small	small	small	Seismic Isolation, or Energy Dissipation
Very Flexible Buildings (steel or concrete frames)	large	normally large (note 1)	normally moderate (note 1)	normally small (note 1)	normally moderate (note 1, note 2)	normally small (note 1)	Energy Dissipation (note 2)

Note 1. Flexible buildings cover a broad range of building types and wide period range. Selection of an appropriate system to reduce earthquake damage depends on the dynamic characteristics of the building in question. Energy dissipation schemes are more likely to be effective for very flexible structures, but either system might be used for semi-rigid and semi-flexible structures.

Note 2. Special detailing may be required to protect elements vulnerable to displacement damage as a result of the moderate interstory displacements.