PROPOSAL 2-118 (2009)

SCOPE: Part 2, Commentary Chapter 18

PROPOSAL FOR CHANGE:

Add Chapter 18 to Part 2, of the 2009 Commentary:

Proposed Chapter is attached. Text is not underlined to allow easier review.

REASON FOR PROPOSAL:

One of the basic tasks of the 2009 NEHRP *Provisions* update is to develop a viable commentary to Part 1. Since Part 1 adopts ASCE 7-05 and lists any exceptions to it, the Commentary is developed in accordance with the format and sections of ASCE 7-05.

TS 3 VOTE:

YES ☐ *Yes with Reservations* *No* ☐ *Not Voting* ☐

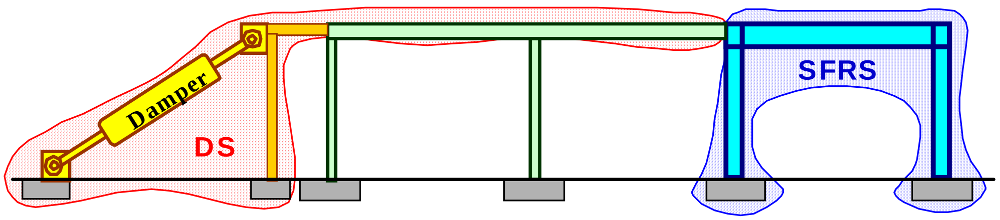
TS 2 developed this commentary chapter and approved for submission. The chapter was edited and has been accepted by TS 2.

Chapter 18
SEISMIC DESIGN REQUIREMENTS FOR STRUCTURES WITH DAMPING SYSTEMS

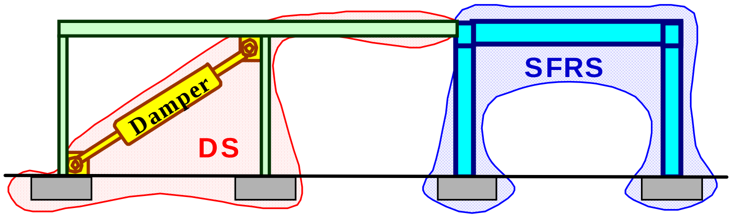
C18.1 GENERAL

The requirements of this chapter apply to all types of damping systems, including both displacement-dependent damping devices of hysteretic or friction systems and velocity-dependent damping devices of viscous or visco-elastic systems (Soong and Dargush, 1997; Constantinou et al., 1998; Hanson and Soong, 2001). Compliance with these design requirements is intended to produce performance comparable to that for a structure with a conventional seismic-force-resisting system, but the same methods can be used to achieve higher performance.

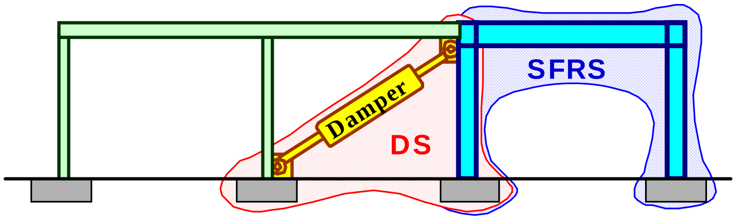
The damping system is defined separately from the seismic-force-resisting system, although the two systems may have common elements. As illustrated in Figure C18.1-1, the damping system may be external or internal to the structure and may have no shared elements, some shared elements, or all elements in common with the seismic-force-resisting system. Elements common to the damping system and the seismic-force-resisting system must be designed for a combination of the two loads of the two systems.



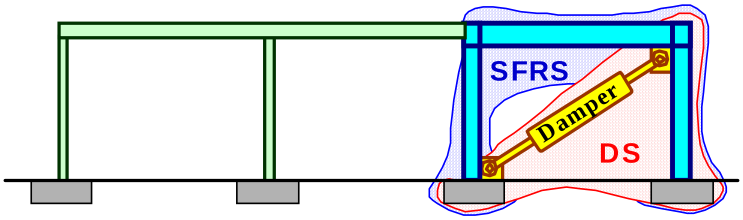
External Damping Devices



Internal Damping Devices - No Shared Elements



Internal Damping Devices - Some Shared Elements



Internal Damping Devices - Common Elements

Figure C18.1-1 Damping system (DS) and seismic-force-resisting system (SFRS) configurations

C18.2 GENERAL DESIGN REQUIREMENTS

C18.2.2 System Requirements. Structures with a damping system must have a seismic-force-resisting system that provides a complete load path. The seismic-force-resisting system must comply with the requirements of this standard, except that the damping system may be used to meet drift limits.

[moved from below] The seismic-force-resisting system without the damping system (as if damping devices were disconnected) must be designed for not less than 75 percent of the base shear of a conventional structure (and not less than 100 percent, if the structure is highly irregular), using an *R* factor as defined in Table 12.2-1. This approach provides safety in the event of damping system malfunction and produces a composite system with sufficient stiffness and strength to have controlled lateral displacement response.

The damping system must be designed for the actual (unreduced) earthquake forces (such as, peak force occurring in damping devices). For certain elements of the damping system, other than damping devices, limited yielding is permitted provided such behavior does not affect damping system function or exceed the amount permitted for elements of conventional structures by this standard.

C18.2.3 Ground Motion. [moved from below] Similar to seismic isolators, damping devices must have design and prototype testing for maximum considered earthquake displacements, velocities, and forces.

C18.2.4 Procedure Selection. This chapter provides linear static and response spectrum analysis methods for design of structures that meet certain configuration and other limiting criteria (for example, at least two damping devices at each story configured to resist torsion). Additional nonlinear response history analysis is used to confirm peak response for structures not meeting the criteria for linear analysis (and for structures close to major faults).

New analysis methods are presented for structures with dampers based on nonlinear “pushover” characterization of the structure and calculation of peak response using effective (secant) stiffness and effective damping properties of the first (pushover) mode in the direction of interest. These are the same concepts as those used in Chapter 17 to characterize the force-deflection properties of isolation systems, modified to incorporate explicitly the effects of ductility demand (post-yield response) and higher-mode response of structures with dampers. Unlike isolated structures, but like conventional structures, structures with dampers generally yield during strong ground shaking, and their performance can be influenced strongly by response of higher modes.

The response spectrum and equivalent lateral force procedures presented in this standard have several simplifications and limits, as outlined below:

1. A multi-degree-of-freedom (MDOF) structure with a damping system can be transformed into equivalent single-degree-of-freedom (SDOF) systems using modal decomposition procedures. This assumes that the collapse mechanism for the structure is a single-degree-of-freedom mechanism so that the drift distribution over height can be estimated reasonably using either the first mode shape or another profile, such as an inverted triangle. Such procedures do not strictly apply to either yielding buildings or buildings that are non-proportionally damped.
2. The response of an inelastic single-degree-of-freedom system can be estimated using equivalent linear properties and a 5-percent-damped response spectrum. Spectra for damping greater than 5 percent can be established using damping coefficients, and velocity-dependent forces can be established either by using the pseudo-velocity and modal information or by applying correction factors to the pseudo-velocity.
3. The nonlinear response of the structure can be represented by a bilinear hysteretic relationship with zero post-elastic stiffness (elasto-plastic behavior).

4. The yield strength of the structure can be estimated either by performing simple plastic analysis or by using the specified minimum seismic base shear and values of R, Ω_0, and C_d.
5. Higher modes need to be considered in the equivalent lateral force procedure in order to capture their effects on velocity-dependent forces. This is reflected in the residual mode procedure.

FEMA 440 (Applied Technology Council, 2005) presents a review of simplified procedures for the analysis of yielding structures. The combined effects of the simplifications mentioned above are reported by Ramirez et al. (2001) and Pavlou and Constantinou (2004) based on studies of 3-story and 6-story buildings with damping systems designed by the procedures of this standard. The response spectrum and equivalent lateral force procedures of this standard are found to provide conservative predictions of drift and predictions of damper forces and member actions that are of acceptable accuracy when compared to results of nonlinear dynamic response history analysis. When designed in accordance with this standard, structures with damping systems are expected to have structural performance at least as good as that of structures without damping systems. Pavlou and Constantinou (2006) report that structures with damping systems designed in accordance with this standard provide the benefit of reduced secondary system response, although this benefit is restricted to systems with added viscous damping.

C18.3 NONLINEAR PROCEDURES

For designs in which the seismic-force-resisting-system is essentially elastic (assuming an overstrength of 50 percent), the only nonlinear characteristics that must be modeled in the analysis are those of the damping devices. For designs in which the seismic-force-resisting system will yield, the post-yield behavior of the structural elements must be modeled explicitly.

C18.4 RESPONSE SPECTRUM PROCEDURES and C18.5 EQUIVALENT LATERAL FORCE PROCEDURE

Effective Damping

In this standard the reduced response of a structure with a damping system is characterized by the damping coefficient, B, based on the effective damping, β, of the mode of interest. This is the same approach as that used for isolated structures. Like isolation, effective damping of the fundamental-mode of a damped structure is based on the nonlinear force-deflection properties of the structure. For use with linear analysis methods, nonlinear properties of the structure are inferred from the overstrength factor, Ω_0, and other terms.

Figure C18.4-1 illustrates reduction in design earthquake response of the fundamental mode due to increased effective damping (represented by coefficient, B_{1D}). The capacity curve is a plot of the nonlinear behavior of the fundamental mode in spectral acceleration-displacement coordinates. The reduction due to damping is applied at the effective period of the fundamental mode of vibration (based on the secant stiffness).

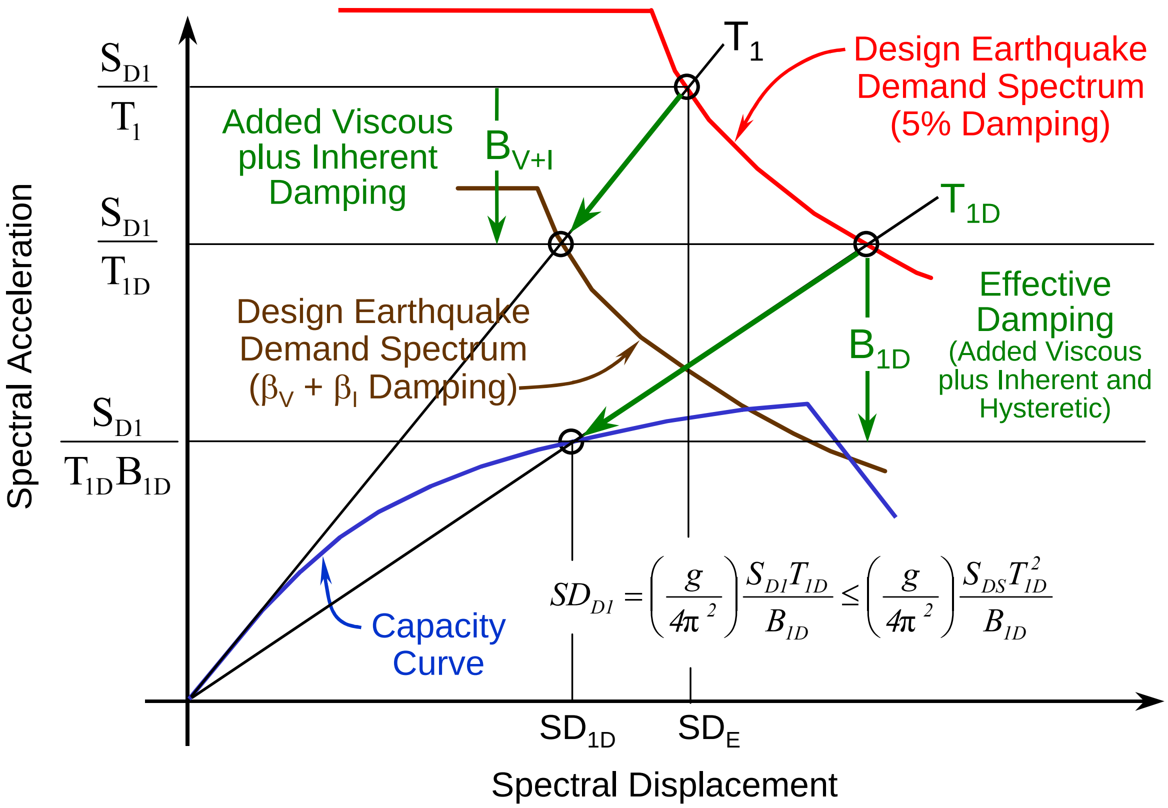


Figure C18.4-1. Effective damping reduction of design demand

In general, effective damping is a combination of three components:

1. Inherent Damping (β_I)—Inherent damping of the structure at or just below yield, excluding added viscous damping (typically assumed to be 5 percent of critical for structural systems without dampers).

2. Hysteretic Damping (β_H)—Post-yield hysteretic damping of the seismic-force-resisting system at the amplitude of interest (taken as 0 percent of critical at or below yield).

3. Added Viscous Damping (β_V)—Viscous component of the damping system (taken as 0 percent for hysteretic or friction-based damping systems).

Both hysteretic damping and added viscous damping are amplitude-dependent, and the relative contributions to total effective damping change with the amount of post-yield response of the structure. For example, adding dampers to a structure decreases post-yield displacement of the structure and, hence, decreases the amount of hysteretic damping provided by the seismic-force-resisting system. If the displacements are reduced to the point of yield, the hysteretic component of effective damping is zero, and the effective damping is equal to inherent damping plus added viscous damping. If there is no damping system (as in a conventional structure), effective damping simply equals inherent damping (typically assumed to be 5 percent of critical for most conventional structures).

Linear Analysis Methods

The chapter specifies design earthquake displacements, velocities, and forces in terms of design earthquake spectral acceleration and modal properties. For equivalent lateral force (ELF) analysis, response is defined by two modes: the fundamental mode and the residual mode. The residual mode is a new concept used to approximate the combined effects of higher modes. While typically of secondary importance to story drift, higher modes can be a significant contributor to story velocity and, hence, are important for design of velocity-dependent damping devices. For response spectrum analysis, higher modes are explicitly evaluated.

For both the ELF and the response spectrum analysis procedures, response in the fundamental mode in the direction of interest is based on assumed nonlinear (pushover) properties of the structure. Nonlinear (pushover) properties, expressed in terms of base shear and roof displacement, are related to building capacity, expressed in terms of spectral coordinates, using mass participation and other fundamental-mode factors shown in Figure C18.4-2. The conversion concepts and factors shown in Figure C18.4-2 are the same as those defined in Chapter 9 of *Seismic Rehabilitation of Existing Buildings* (ASCE 41), which addresses seismic rehabilitation of a structure with damping devices.

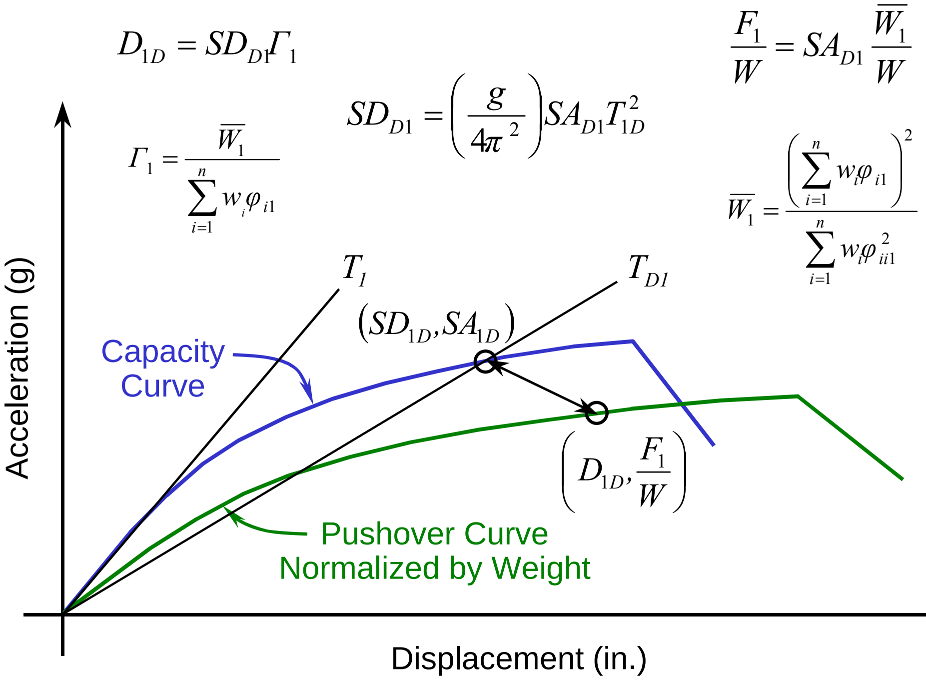


Figure C18.4-2. Pushover and capacity curves

Where using linear analysis methods, the shape of the fundamental-mode pushover curve is not known, so an idealized elasto-plastic shape is assumed, as shown in Figure C18.4-3. The idealized pushover curve is intended to share a common point with the actual pushover curve at the design earthquake displacement, D_{1D}. The idealized curve permits definition of the global ductility demand due to the design earthquake, μ_D, as the ratio of design displacement, D_{1D}, to yield displacement, D_Y. This ductility factor is used to calculate various design factors; it must not exceed the ductility capacity of the seismic-force-resisting system, μ_{max}, which is calculated using factors for conventional structural response. Design examples using linear analysis methods have been developed and found to compare well with the results of nonlinear time history analysis (Ramirez et al., 2001).

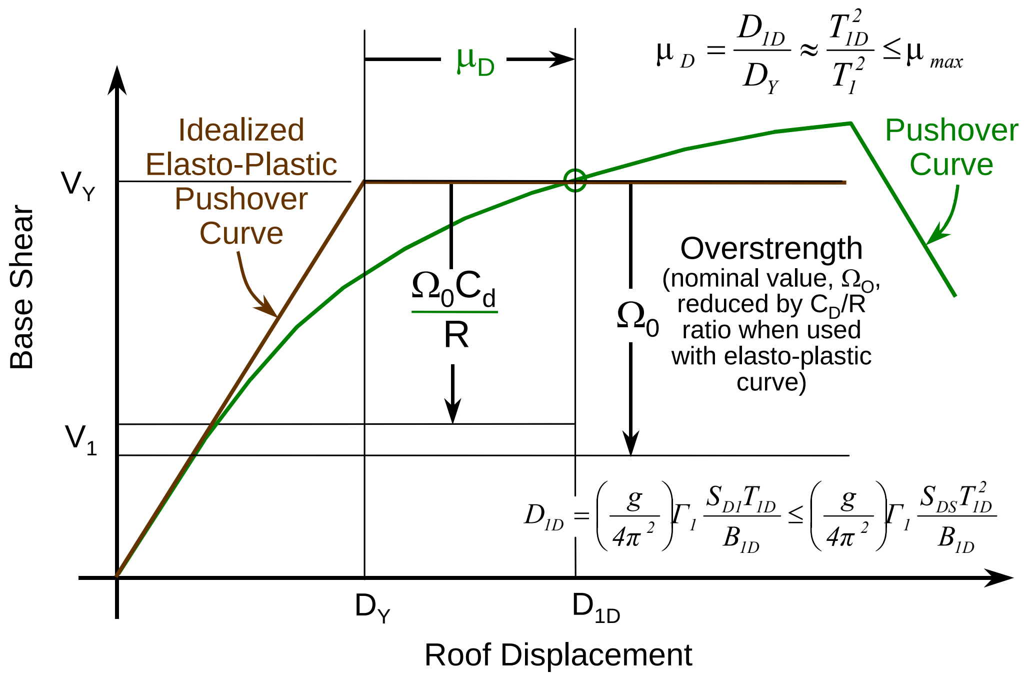


Figure C18.4-3. Idealized elasto-plastic pushover curve used for linear analysis

Elements of the damping system are designed for fundamental-mode design earthquake forces corresponding to a base shear value of V_Y (except that damping devices are designed and prototypes tested for maximum considered earthquake response). Elements of the seismic-force-resisting system are designed for reduced fundamental-mode base shear, V_1, where force reduction is based on system overstrength (represented by Ω_0), multiplied by C_d/R for elastic analysis (where actual pushover strength is not known). Reduction using the ratio C_d/R is necessary because this standard provides values of C_d that are less than those for R. Where the two parameters have equal value and the structure is 5 percent damped under elastic conditions, no adjustment is necessary. Because the analysis methodology is based on calculating the actual story drifts and damping device displacements (rather than the displacements calculated for elastic conditions at the reduced base shear and then multiplied by C_d, an adjustment is needed). Since actual story drifts are calculated, the allowable story drift limits of Table 12.12-1 are multiplied by R/C_d before use.

C18.6 DAMPED RESPONSE MODIFICATION

C18.6.1 Damping Coefficient

Values of the damping coefficient B in Table 18.6-1 for design of damped structures are the same as those in Table 17.5-1 for isolated structures at damping levels up to 20 percent, but extend to higher damping levels based on results presented in Ramirez et al. (2001). Table C18.6-1 compares values of the damping coefficient as found in this standard and various resource documents and codes. FEMA 440 and the draft of Eurocode 8 present equations for the damping coefficient, B, whereas the other documents present values of B in tabular format.

The equation in FEMA 440 is

$$B = \frac{4}{5.6 - \ln(100\beta)}$$

The equation in Eurocode 8 is

$$B = \sqrt{\frac{0.05 + \beta}{0.10}}$$

TABLE C18.6-1 Values of Damping Coefficient *B*

Effective Damping, β (%)	Table 17.5-1, 1999 AASHTO, 2001 CBC(seismically isolated structures)	Table 18.6-1 (structures with damping systems)	FEMA 440	EUROCODE 8
≤ 2	0.8	0.8	0.8	0.8
5	1.0	1.0	1.0	1.0
10	1.2	1.2	1.2	1.2
20	1.5	1.5	1.5	1.6
30	1.7	1.8	1.8	1.9
40	1.9	2.1	2.1	2.1
50	2.0	2.4	2.4	2.3

C18.6-2 Effective Damping

The effective damping is calculated assuming structural system exhibits perfectly bi-linear hysteretic behavior characterized by the effective ductility demand, μ, as described in Ramirez et al. (2001). Effective damping is adjusted using of the hysteresis loop adjustment factor, q_H, which is the actual area of the hysteresis loop divided by the area of the assumed perfectly bi-linear hysteretic loop. In general, values of this factor are less than unity. In Ramirez et al. (2001) expressions for this factor (which they call Quality Factor) are too complex to serve as a simple rule. Equation 18.6-5provides a simple estimate of this factor. The equation predicts correctly the trend in the constant acceleration domain of the response spectrum, and it is believed to be conservative for flexible structures.

C18.7 SEISMIC LOAD CONDITIONS AND ACCEPTANCE CRITERIA

C18.7.2.5 Seismic Load Conditions and Combination of Modal Responses. Seismic design forces in elements of the damping system are calculated at three distinct stages: maximum displacement, maximum velocity, and maximum acceleration. All three stages need to be checked for structures with velocity-dependent damping systems. For displacement-dependent damping systems, the first and third stages are identical, whereas the second stage is inconsequential.

Force coefficients C_{mFD} and C_{mFV} are used to combine the effects of forces calculated at the stages of maximum displacement and maximum velocity to obtain the forces at maximum acceleration.

The coefficients are presented in tabular form based on analytic expressions presented in Ramirez et al. (2001), and account for nonlinear viscous behavior and inelastic structural system behavior.

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