

Chapter 15 Commentary

STRUCTURES WITH DAMPING SYSTEMS

Background. Chapter 15, Structures with Damping Systems, appears for the first time in the body of the 2003 *Provisions*, having first appeared as an appendix (to Chapter 13) in the 2000 *Provisions*. The appendix was developed by Technical Subcommittee 12 (TS 12) of the Provision Update Committee (PUC) during the 2000 update cycle to provide a basis for designing structures with damping systems that is consistent with the *NEHRP Provisions*, in particular structures with seismic (base) isolation systems. Voting members of TS 12 during the 2000 update were Dr. Charles Kircher (TS 12 Chair and PUC representative), Dr. Michael Constantinou (PUC representative), Dr. Ian Aiken, Dr. Robert Hanson, Mr. Martin Johnson, Dr. Andrew Taylor, and Dr. Andrew Whittaker

During the 2000 update cycle, the primary resource documents for the design of structures with dampers were the *NEHRP Guidelines for Seismic Rehabilitation of Buildings* (FEMA 273, 1997) and the *NEHRP Commentary on the Guidelines for the Seismic Rehabilitation of Buildings* (FEMA 274, 1997). While suitable for the performance-based design, terms, methods of analysis and response limits of the *NEHRP Guidelines* for existing buildings do not match those of the *NEHRP Provisions* for new structures. Accordingly, TS-12 developed new provisions, in particular new linear analysis methods, for design of structures with dampers.

New analysis methods were developed 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 same concepts used in Chapter 13 to characterize the force-deflection properties of isolation systems, modified to explicitly incorporate the effects of ductility demand (post-yield response) and higher-mode response of structures with dampers. In contrast to isolated structures, structures with dampers are in general expected to yield during strong ground shaking (similar to conventional structures), and their performance can be significantly influenced by response of higher modes.

During the 2000 cycle, analysis methods were evaluated using design examples. Response calculated using linear analysis was found to compare well with the results of nonlinear time history analysis (Ramirez, 2001). Additional design examples illustrating explicit “pushover” modeling of the structure may be found in Chapter 9 commentary of FEMA 274. The reader is also referred to Ramirez et al. (2002a, 2002b, 2003) and Whittaker et al. (2003) for a detailed exposition of the analysis procedures in this chapter, background research studies, examples of application and an evaluation of accuracy of the linear static and response spectrum analysis methods.

The balance of this section provides background on the underlying philosophy used by TS12 to develop the chapter, the definition the damping system, the concept of effective damping, and the calculation of earthquake response using either linear or nonlinear analysis methods.

Design Philosophy. The basic approach taken by TS12 in developing the chapter for structures with damping systems is based on the following concepts:

1. The chapter is applicable 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 (Constantinou et al. 1998, Hanson and Soong, 2001)
2. The chapter provides minimum design criteria with performance objectives comparable to those for a structure with a conventional seismic-force-resisting system (but also permits design criteria that will achieve higher performance levels).

3. The chapter requires structures with a damping system to have a seismic-force-resisting system that provides a complete load path. The seismic-force-resisting system must comply with the requirements of the *Provisions*, except that the damping system may be used to meet drift limits.
4. The chapter requires design of damping devices and prototype testing of damper units for displacements, velocities, and forces corresponding to those of the maximum considered earthquake (same approach as that used for structures with an isolation system).
5. The chapter provides linear static and response spectrum analysis methods for design of most structures that meet certain configuration and other limiting criteria (for example, at least two damping devices at each story configured to resist torsion). The chapter requires additional nonlinear response history analysis to confirm peak response for structures not meeting the criteria for linear analysis (and for structures close to major faults).

Damping system. The chapter defines the damping system as:

“The collection of structural elements that includes all individual damping devices, all structural elements or bracing required to transfer forces from damping devices to the base of the structure, and all structural elements required to transfer forces from damping devices to the seismic-force-resisting system.”

The damping system is defined separately from the seismic-force-resisting system, although the two systems may have common elements. As illustrated in Figure C15-1, 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.

The seismic-force-resisting system may be thought of as a collection of lateral-force-resisting elements of the structure if the damping system was not functional (as if damping devices were disconnected). This system is required to be designed for not less than 75 percent of the base shear of a conventional structure (not less than 100 percent, if the structure is highly irregular), using an *R* factor as defined in Table 4.3-1. This system provides both a safety net against damping system malfunction as well as the stiffness and strength necessary for the balanced lateral displacement of the damped structure.

The chapter requires the damping system to be designed for the actual (non-reduced) 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 by the *Provisions* for elements of conventional structures.

The chapter defines a damping device as:

“A flexible structural element of the damping system that dissipates energy due to relative motion of each end of the device. Damping devices include all pins, bolts, gusset plates, brace extensions, and other components required to connect damping devices to other elements of the structure. Damping devices may be classified as either displacement-dependent or velocity-dependent, or a combination thereof, and may be configured to act in either a linear or nonlinear manner.”

Following the same approach as that used for design of seismic isolators, damping devices must be designed for maximum considered earthquake displacements, velocities, and forces. Likewise, prototype damper units must be fully tested to demonstrate adequacy for maximum considered earthquake loads and to establish design properties (such as effective damping).

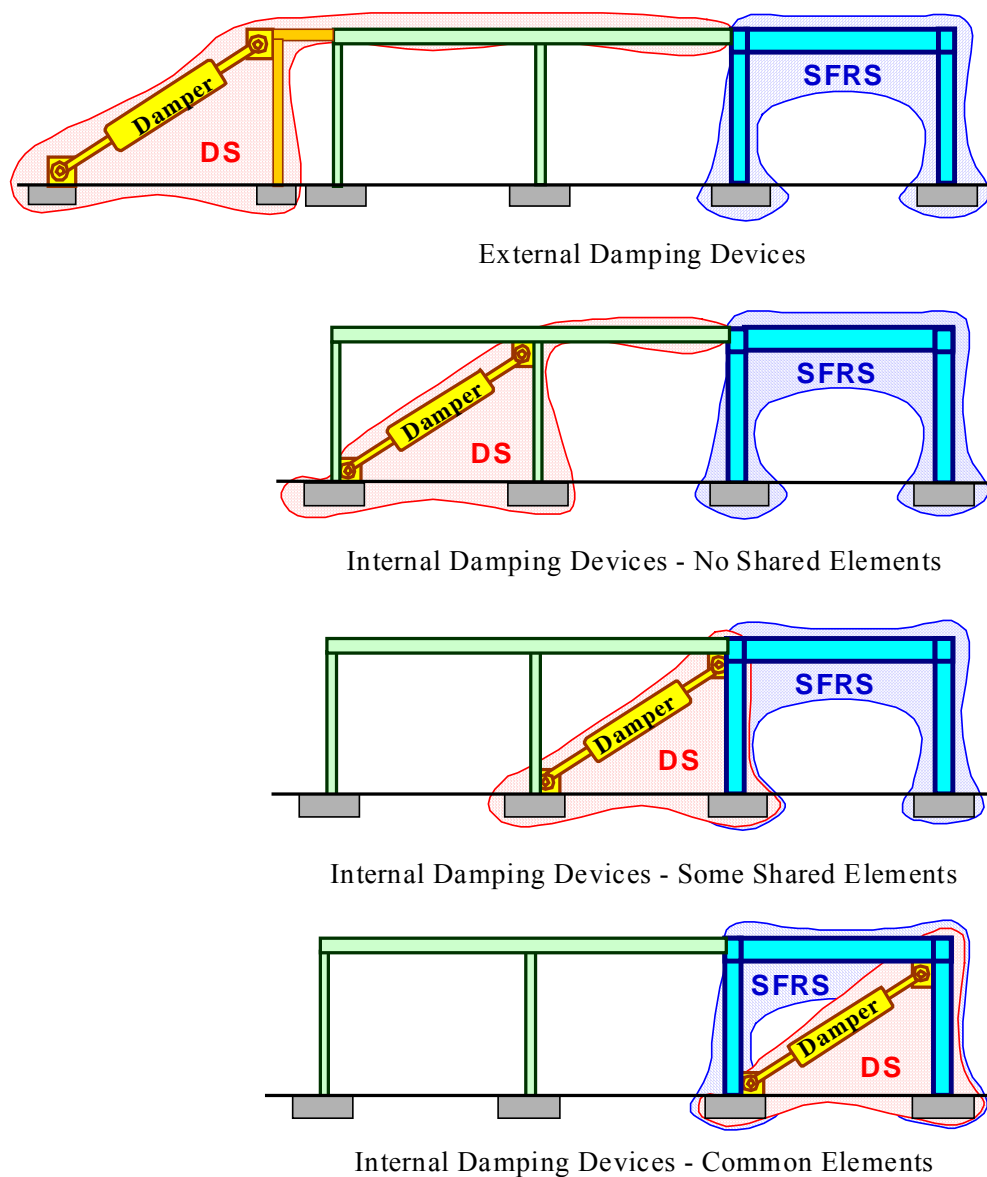


Figure C15-1. Damping system (DS) and seismic-force-resisting system (SFRS) configurations.

Effective Damping. The chapter reduces the response of a structure with a damping system by the damping coefficient, B , based on the effective damping, β , of the mode of interest. This is the same approach as that used by the *Provisions* for isolated structures. Values of the B coefficient recommended for design of damped structures are the same as those in the *Provisions* for isolated structures at damping levels up to 30 percent, but now extend to higher damping levels based on the results presented in Ramirez et al. (2001). 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 overstrength, Ω_0 , and other terms of the *Provisions*. For nonlinear analysis methods, properties of the structure would be based on explicit modeling of the post-yield behavior of elements.

Figure C15-2 illustrates reduction in design earthquake response of the fundamental mode due to effective damping coefficient, B_{1D} . The capacity curve is a plot of the nonlinear behavior of the

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 C15-3. The conversion concepts and factors shown in Figure C15-3 are the same as those defined in Chapter 9 of *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (FEMA 273), which addresses seismic rehabilitation of a structure with damping devices.

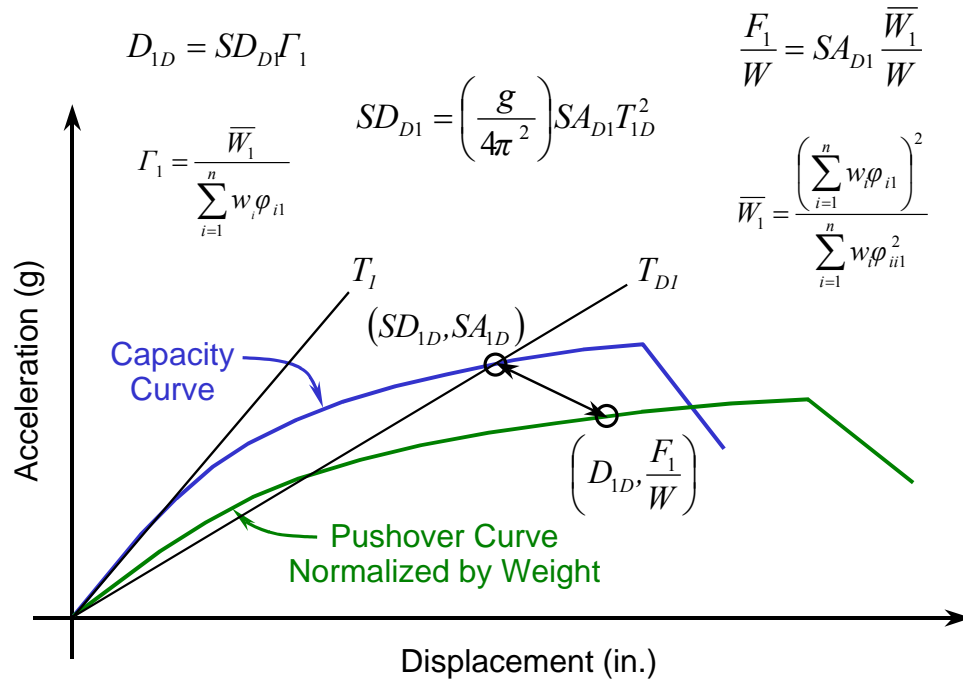


Figure C15-3. Pushover and capacity curves.

When using linear analysis methods, the shape of the fundamental-mode pushover curve is not known and an idealized elasto-plastic shape is assumed, as shown in Figure C15-4. The idealized pushover curve shares a common point with the actual pushover curve at the design earthquake displacement, D_{1D} . The idealized curve permits defining global ductility demand due to the design earthquake, μ_D , as the ratio of design displacement, D_{1D} , to the yield displacement, D_Y . This ductility factor is used to calculate various design factors and to set limits on the building ductility demand, μ_{max} , which limits are consistent with conventional building response limits. 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).

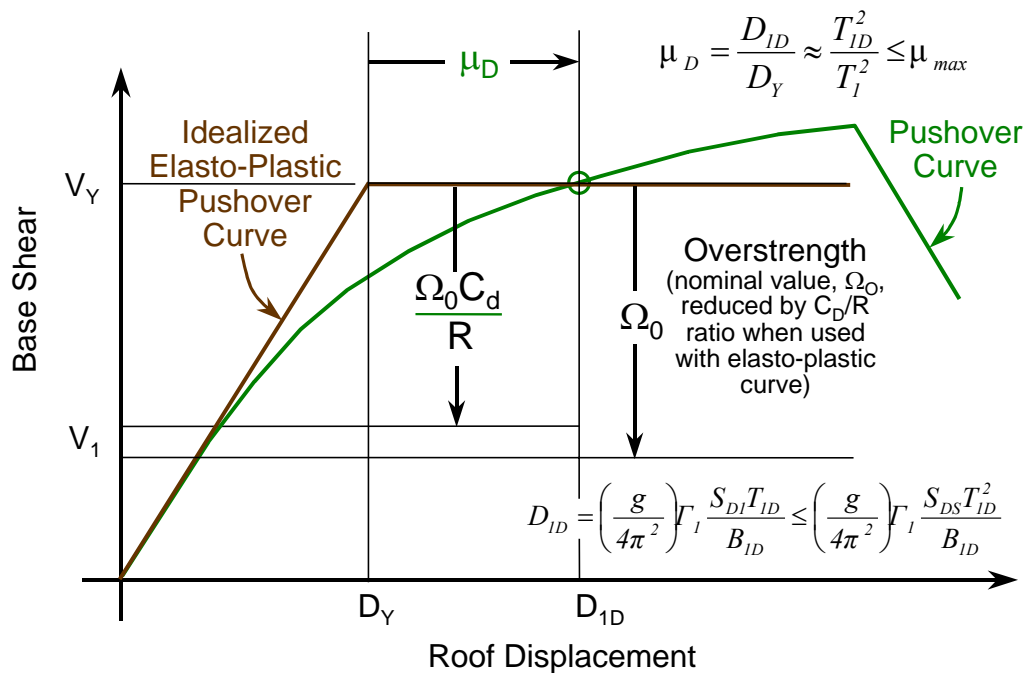


Figure C15-4. Idealized elasto-plastic pushover curve used for linear analysis.

The chapter requires elements of the *damping system* to be designed for actual 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, Ω_0 , conservatively decreased by the ratio, C_d/R , for elastic analysis (when actual pushover strength is not known).

Nonlinear analysis methods. The chapter specifies procedures for the nonlinear response history analyses and a nonlinear static procedure. For designs in which the seismic-force-resisting-system will remain elastic, only the nonlinear damping device characteristics need to be modeled for these analyses.

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