

## T2-5-a-3

# U.S. CODE DEVELOPMENT OF STRUCTURES WITH DAMPING SYSTEMS.

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### Abstract:

Many applications of damper devices in both new and existing buildings in both United States and Japan have resulted from extensive development efforts. The increased usage of this technology has created a demand for design guidance and building codes to specify their use in the United States. This paper provides a summary of the code development activities for the 2003 NEHRP by the Building Seismic Safety Council.

## 1. Introduction

In 1993, the Energy Dissipation Working Group (EDWG) of the Base Isolation Subcommittee of the Structural Engineers Association of Northern California (SEAONC) started to meet the demand for design guidance. They developed a document that proposed tentative design requirements applicable to a wide range of system hardware (Whittaker et al, 1993) and recommended a testing program to verify device performance. The scope included metallic, friction, viscoelastic, and viscous devices.

The general philosophy of the EDWG document was to confine inelastic deformation primarily to the energy dissipation devices, while the main structural members remain elastic for the Design Basis Earthquake (DBE). Furthermore, since passive energy dissipation technology was still relatively new, a conservative approach was taken on many issues. For example, an experienced independent engineering review panel was required for all projects to conduct a review of the energy dissipation system design and the associated prototype testing programs.

A simpler approach was included as Appendix to Chapter 2 of *FEMA 222A NEHRP Recommended Provisions for Seismic Regulations for New Buildings, 1994 Edition*. The purpose of this Appendix was to introduce potential users to these new and relevant techniques, but it was not to be considered a code. It used an equivalent viscous damping approach that required nonlinear time-history analyses for all systems using devices other than linear velocity proportional devices. It also recommended a testing program similar to that proposed by EDWG.

During this period of time a significant effort funded by FEMA was underway to create technical guidelines for the seismic upgrading of buildings. Energy dissipation systems were included in the range of available techniques to improve seismic performance. The results of

these efforts were published in Chapter 9 of *FEMA 273 NEHRP Guidelines for the Seismic Rehabilitation of Buildings, October 1997*. This document takes a performance-based approach to system upgrades. Chapter 9 outlines linear static, linear dynamic, nonlinear static, and nonlinear dynamic procedures for energy dissipation systems in parallel with the techniques used in the other design and analysis chapters in FEMA 273. Chapter 9 also specifies recommended quality control and prototype testing programs, and an independent panel for review of the system design and testing programs. This guideline was more extensive than the EDWG guideline and was more extensive than the FEMA 222A approach, but it could not be referenced or quoted for the proposed *FEMA 302 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, 1997 Edition* because FEMA 273 had not been published or made generally available at the time *FEMA 302* went to ballot. As a result, *FEMA 302 Appendix to Chapter 13* entitled “Passive Energy Dissipation Systems” only provided brief statements as to the benefits of damping for improved performance, suggested rational design procedures be used, and recommended an independent panel for design and test program review. It was recognized by all participants that this Appendix was only a placeholder for more thorough requirements in the 2000 edition of the *Recommended Provisions*

The Appendix to Chapter 13 of *FEMA 368 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, 2000 Edition* is entitled “Structures with Damping Systems” was published in March 2001. It was intended to be applicable to all types of energy dissipation systems, to provide design criteria comparable to conventional design performance, to provide design criteria for enhanced seismic performance, to distinguish between the design of members that are part of the energy dissipation system and the design of members independent of that system. It provides a static design approach when the structure and energy dissipation system satisfy configuration and other restrictive criteria. It requires an independent engineering review of the design and testing programs.

## **2. Appendix 13 in FEMA 368 (NEHRP 2000)**

In preparation for the 2003 Edition of the *Recommended Provisions, FEMA 368* was reformatted to eliminate duplication and clarify the design requirements. This paper quotes from the reformatted version of *FEMA 368*. The Appendix to Chapter 13 format follows the basic *FEMA 368* approach and where appropriate uses the general provisions of *FEMA 368* without restating them. In this discussion any differences in the recommended procedures between the different Seismic Use Group and Seismic Design Category classes have been ignored. The emphasis in this paper is on the technical provisions in the design procedures and their relationship to engineering principles. The following definitions are used in *FEMA 368 Appendix to Chapter 13*.

- *Seismic-force-resisting system* is that part of the structural system that has been considered in the design to provide the required resistance to the seismic forces.
- *Damping device* is a flexible structural element that dissipates energy and includes all pins, bolts, gusset plates, brace extensions, and other components necessary to connect the devices to the structure.

- *Damping system* is the collection of all structural elements and devices required to transfer forces from the devices to the foundation, and all structural elements required to transfer forces from the devices to the seismic-force-resisting system.

The approach for the equivalent lateral force procedure assumes that all calculations can be made without a computer or spreadsheet. To do this a number of simplifying assumptions were made. The following will summarize some of the key elements of the recommended code procedure and assumptions.

## 2.1 General Design Requirements.

The structural system considers both the basic requirements of the *seismic-force-resisting system* and the *damping system*. The key to this consideration is the reduction in forces carried by the *seismic-force-resisting system* due to the contribution of the *damping system* while recognizing the appropriate combination of forces in the two systems. For linear viscous damping systems where the damping forces are proportional to velocity and the primary system forces are related to displacements, the maximum combination of forces does not occur when one is at zero and the other is at a maximum. Thus, these forces must be combined in an appropriate way. The displacements of the coupled systems are compared with the code allowable displacements.

## 2.2 Seismic-force-resisting system.

The following which is copied from the reformatted *FEMA 368* provides that the basic lateral resisting system can be designed for as little as 75% of the applicable code lateral forces subject to two framing restrictions:

The design of the seismic-force-resisting system in each direction shall satisfy the requirements of Sec. A13.7 and the following:

1. *The seismic base shear used for design of the seismic-force-resisting system shall not be less than  $V_{min}$ , where  $V_{min}$  is determined as the greater of the values computed using Eq. A13.2-1 and A13.2-2 as follows:*

$$V_{min} = V / B_{v+1} \quad (A13.2-1)$$

$$V_{min} = 0.75 V \quad (A13.2-2)$$

where:

$V$  = seismic base shear in the direction of interest, determined in accordance with Sec. 5.2

$B_{v+1}$  = numerical coefficient as set forth in Table A13.3-1 for effective damping equal to the sum of viscous damping in the fundamental mode of vibration of the structure in the direction of interest,  $\beta_{vm}$  ( $m=1$ ), plus inherent damping,  $\beta_i$ , and period of structure equal to  $T_1$ .

**Exception:** *The seismic base shear used for design of the seismic-force-resisting system shall not be taken as less than 1.0  $V$ , if either of the following conditions apply:*

- a. *In the direction of interest, the damping system has less than two damping devices on each floor level, configured to resist torsion.*

- b. The seismic-force-resisting system has plan irregularity Type Ib (Table 4.3-2) or vertical irregularity Type Ib (Table 4.3-3).*
- 2. Minimum strength requirements for elements of the seismic-force-resisting system that are also elements of the damping system or are otherwise required to resist forces from damping devices shall meet the additional requirements of Sec.A13.7.2.*

### **2.3 Damping system.**

Elements of the damping system shall remain elastic unless it is shown by analysis or test that inelastic response of the elements would not adversely affect damping system function.

### **2.4 Procedure Selection.**

Nonlinear procedures, linear procedures or a combination of linear and nonlinear procedures and equivalent lateral load procedures are allowed subject to certain restrictions.

#### **2.4.1 Nonlinear Procedures**

Response history analysis with nonlinear structural members and nonlinear damping devices, linear structural members with nonlinear damping devices, linear structural members with linear damping devices are all permitted without restrictions beyond those of the basic seismic-force-resisting system. A nonlinear response history is required to confirm the performance of any design where the design spectral acceleration at one second is equal to or greater than 0.6 g. Constantinou et al. (1998), Hanson and Soong (2001), Scholl (1993), and Whittaker et al (1993) provide detailed information to implement procedures involving linear and nonlinear response history procedures. A nonlinear static procedure (nonlinear pushover analysis) is also permitted in combination with the equivalent lateral force procedure to be described later.

#### **2.4.2 Response Spectrum Procedure**

The response spectrum procedure is permitted provided that (1) the damping system has at least two damping devices in each story in the direction of interest configured to resist torsion, and (2) the total effective damping of the fundamental mode in the direction of interest is not greater than 35 percent of critical.

#### **2.4.3 Equivalent Lateral Force Procedure**

The equivalent lateral force procedure is permitted provided that (1) the damping system has at least two damping devices in each story in the direction of interest configured to resist torsion, (2) the total effective damping of the fundamental mode in the direction of interest is not greater than 35 percent of critical, (3) the seismic-force-resisting system does not have vertical or plan irregularities, (4) the floor diaphragms are rigid, and (5) the height of the structure above its base does not exceed 30 meters (100 feet). One unique concept is the introduction of the residual mode in the static equivalent lateral force procedure. The fundamental mode and the residual mode are combined in a square-root-sum-of-the-squares approach for comparison with the minimum design base shear. A description of this development and verification of its accuracy are provided by Ramirez et al (2001). Specifically from FEMA 368

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### A13.4.2 Seismic-force-resisting system

**A13.4.2.1 Seismic base shear.** The seismic base shear,  $V$ , of the seismic-force-resisting system in a given direction shall be determined as the combination of the two modal components,  $V_1$  and  $V_R$ , in accordance with the following equation:

$$V = \sqrt{V_1^2 + V_R^2} \geq V_{min} \quad (A13.4-1)$$

where:

$V_1$  = design value of the seismic base shear of the fundamental mode in a given direction of response, as determined in Sec. A13.4.2.2,

$V_R$  = design value of the seismic base shear of the residual mode in a given direction, as determined in Sec. A13.4.2.6, and

$V_{min}$  = minimum allowable value of base shear permitted for design of the seismic-force-resisting system of the structure in direction of the interest, as determined in Sec. A13.2.2.1.

**A13.4.2.2 Fundamental mode base shear.** The fundamental mode base shear,  $V_1$ , shall be determined in accordance with the following equation:

$$V_1 = C_{S1} \bar{W}_1 \quad (A13.4-2)$$

where:

$C_{S1}$  = the fundamental mode seismic response coefficient, as determined in Sec. A13.4.2.4, and

$\bar{W}_1$  = the effective fundamental mode gravity load including portions of the live load as defined by Eq. 5.3-2 for  $m = 1$ .

**A13.4.2.6 Residual mode base shear.** Residual mode base shear,  $V_R$ , shall be determined in accordance with Eq. A13.4-10 as follows:

$$V_R = C_{SR} \bar{W}_R \quad (A13.4-10)$$

where:

$C_{SR}$  = the residual mode seismic response coefficient as determined in Sec. A13.4.2.8, and

$\bar{W}_R$  = the effective residual mode gravity load of the structure determined using Eq. A13.4-13.

**A13.4.2.7 Residual mode properties.** Residual mode shape,  $\phi_{iR}$ , participation factor,  $\Gamma_R$ , effective gravity load of the structure,  $\bar{W}_R$ , and effective period,  $T_R$ , shall be determined using Eq. A13.4-11 through A13.4-14 as follows:

$$\phi_{iR} = \frac{1 - \Gamma_1 \phi_{i1}}{1 - \Gamma_1} \quad (A13.4-11)$$

$$\Gamma_R = 1 - \Gamma_1 \quad (A13.4-12)$$

$$\bar{W}_R = W - \bar{W}_I \quad (A13.4-13)$$

$$T_R = 0.4T_I \quad (A13.4-14)$$

**A13.4.2.8 Residual mode seismic response coefficient.** The residual mode seismic response coefficient,  $C_{SR}$ , shall be determined in accordance with the following equation:

$$C_{SR} = \left( \frac{R}{C_d} \right) \frac{S_{DS}}{\Omega_0 B_R} \quad (A13.4-15)$$

where:

$B_R$  = Numerical coefficient as set forth in Table A13.3-1 for effective damping equal to  $\beta_R$ , and period of the structure equal to  $T_R$ .

Although used in each step of the process, the primary purpose of the residual mode is to provide a better estimate of the maximum interstory relative velocities for estimating the maximum forces in the viscous damping devices and their supporting members.

#### 2.4.4 Damping System

The effective damping coefficient for the structure is established as a combination of the inherent damping of the structural system, the damping added by installed damping devices and nonlinear hysteretic structural energy dissipation. The equation for this effective damping from the Appendix to Chapter 13, without the subscripts for design or maximum earthquake level considered is

$$\beta_m = \beta_I + \beta_{vm} \sqrt{\mu} + \beta_H \quad (A13.3-1)$$

where  $\beta_m$  is the effective damping in mode  $m$ ,  $\beta_I$  is the inherent damping of the structural system,  $\beta_{vm} \sqrt{\mu}$  is the equivalent viscous damping of the supplemental damping system in mode  $m$ , and  $\beta_H$  is the hysteretic damping of the structural system. This effective damping modifies the structural response by coefficients as given in equation A13.2-1 above. The ductility,  $\mu$ , is a key parameter in both the modal viscous damping and the hysteretic damping terms. In general, the determination of the actual ductility is an iterative process. It starts with an estimate of the displacements or ductilities, establishes a preliminary design, calculates the resulting displacements, compares the assumed and calculated displacements, and then iterates as needed. The *FEMA 368 Appendix to Chapter 13* provides for the maximum ductility that can be assumed for a standard *seismic-force-resisting* system based on its design properties. This provides an upper limit for the preliminary design

**Inherent Damping.** The inherent damping is based on the structural material type, and shall not be taken greater than 5% of critical unless justified by test data or analysis.

**Hysteretic Damping.** This only includes inelastic, hysteretic deformations of the *seismic-force-resisting* system. It does not include hysteretic deformations of the damping devices, which is included as equivalent viscous damping up to the point when the *seismic-force-resisting* system yields. Unless analysis or test data supports other values, the hysteretic damping of higher modes of vibration in the direction of interest shall be taken as zero. The calculation of hysteretic damping of the seismic-force-resisting system and elements of the damping system shall consider pinching and other effects that reduce the area of the hysteresis loop during repeated cycles of earthquake demand.

**Viscous Damping.** All energy dissipated by damping devices is included in this term. For displacement-dependent devices, only the hysteresis area at displacements less than or equal to the structural yield displacement is included in this calculation. This assumes that the hysteretic device energy dissipation after the structure begins yielding is so small relative to the energy dissipation of the structure itself that it can be neglected in determination of the total energy dissipation.

## 2.5 Seismic Load Conditions and Acceptance Criteria

The seismic load conditions and combination of modal responses for the equivalent lateral force procedure and the response spectrum procedure require the consideration of three cases. They are (1) the stage of maximum displacement, (2) the stage of maximum velocity, and (3) the stage of maximum acceleration. Force coefficients are given to account for different damper velocity exponents varying from 0.25 to 1.0 and for ductilities from less than 1.0 to 2.2 and greater. For response history procedures the maximum element forces are calculated directly and compared with appropriate allowable material values.

## 2.6 Design Review and Testing

A review of the design of the *damping* system and related test programs are to be performed by an independent engineering panel of qualified individuals. It stipulates that at least two full-size *damping devices* of each type and size used in the design be tested. Reduced-scale prototype devices can be used to qualify the rate-dependent properties if they are of the same type and materials, manufactured by the same processes, and tested at a similitude-scaled frequency that simulates the full-scale loading rates. At least five fully reversed, sinusoidal cycles at the maximum earthquake displacement and response frequency are required. If the devices have characteristics that vary with temperature, tests at a minimum of three temperatures covering the operating range of the expected temperatures shall be used. A production test program should be established to ensure that the installed devices have the force-velocity-displacement characteristics that fall within the design limits.

## 3. Recommended Modifications to Appendix 13 in FEMA 368

The major change proposed for 2003 is to make this Appendix 13 a Chapter in the *Recommended Provisions*. This will allow its adoption into building standards and model building codes. The remaining proposed changes are primarily reorganization of the design procedures, clarification of specific requirements, and simplification of the requirements in FEMA 368 wherever possible.

## 4. Conclusion

Perhaps the most common complaint about the approach recommended in *FEMA 368 Appendix to Chapter 13* is that it appears too complex and mathematical. The counter argument has been that unless the designer can be assured that the maximum dynamic effects are included in a static procedure, a response history computation will be required. A member of the *FEMA 368 Appendix to Chapter 13* Technical Subcommittee has prepared a spreadsheet for the equivalent lateral force procedure. Comparisons of the spreadsheet results with corresponding response history results have demonstrated the reliability of the procedure.

However, many design firms prefer to use a response history calculation as final verification of the combined system performance. In that case, any reasonable method for preliminary design of the *seismic-force-resisting system* and the *damping system* can be used. The purpose of this paper was not to extol the benefits of adding a damping system to a traditional lateral force resisting system, nevertheless these benefits are clear.

## 5. References

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