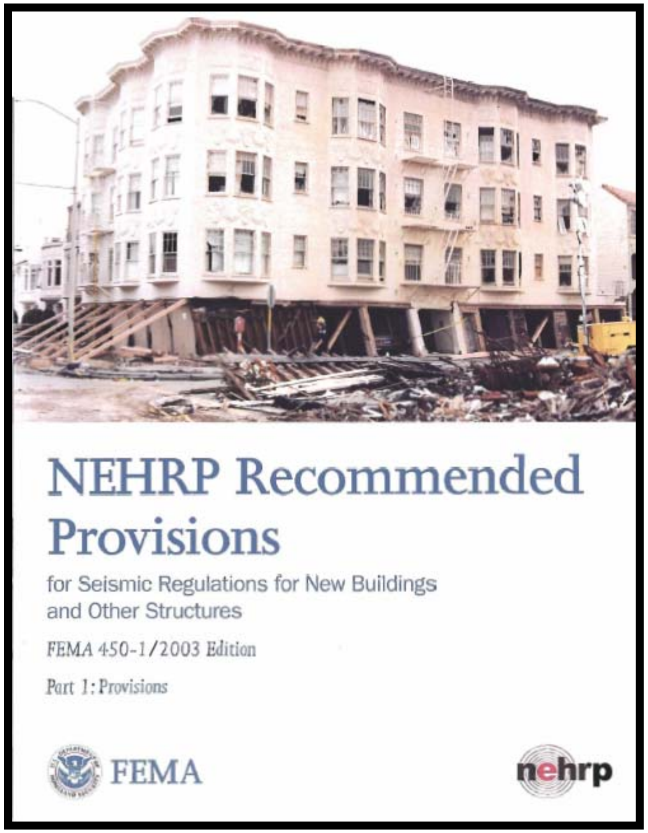
The 2003 NEHRP Recommended Provisions for Structures with Damping Systems



NEHRP Recommended Provisions

for Seismic Regulations for New Buildings
and Other Structures

FEMA 450-1/2003 Edition

Part 1: Provisions

FEMA

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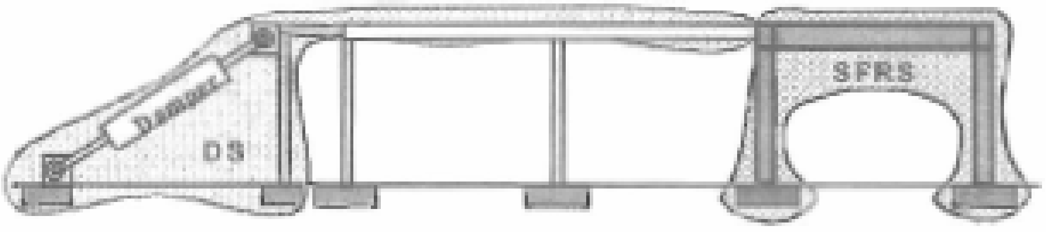
CONTENTS

Scope

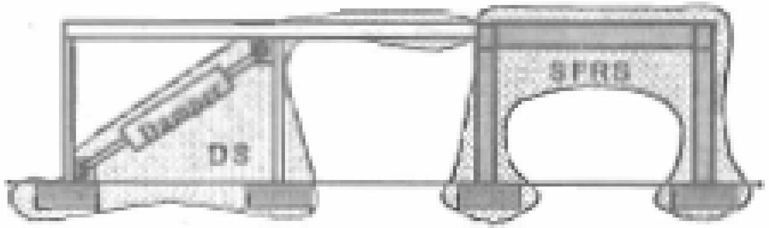
- Building structures equipped with all types of damping systems
  - Hysteretic, viscous, visco-elastic dampers

Design Philosophy

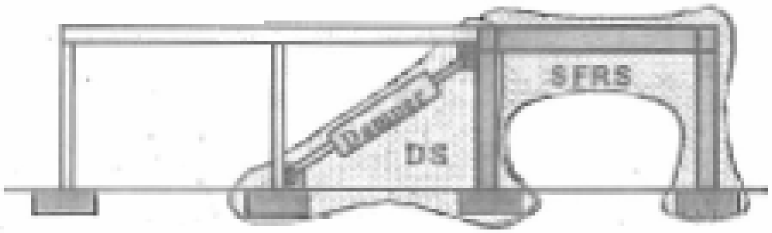
- Seismic-Force-Resisting System (SFRS) that provides a complete load path is required
- Damping of SFRS modified by damping devices
- Damping reduction applied at effective fundamental period of SFRS (based on secant stiffness)
- SFRS must be designed for not less than 75% of the base shear of a conventional structure
- Damping devices designed and tested (prototypes) for displacements, velocities, and forces corresponding to maximum credible earthquake (MCE)



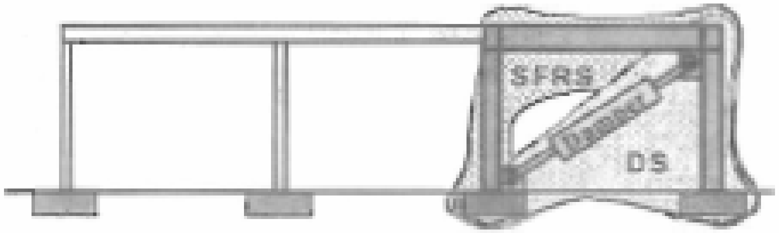
External Damping Devices



Internal Damping Devices - No Shared Elements



Internal Damping Devices - Some Shared Elements



Internal Damping Devices - Common Elements

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

Effective Damping

- Damping system reduces the response of SFRS based on effective damping
- Same approach as NEHRP provisions for base isolation systems
- Effective damping is a combination of 3 components:
  - Inherent Damping, β_I - SFRS at or just below yield
  - Hysteretic damping, β_h – hysteretic dampers + SFRS
  - Added viscous dampers, β_v – viscous dampers
- Hysteretic and added viscous damping is amplitude dependent

Table 15.6-1
Damping Coefficient, B_{V+I}, B_{1D}, B_R, B_{1M}, B_{mD}, or B_{mM}

Effective Damping, β (percentage of critical)	B_{V+I}, B_{1D}, B_R, B_{1M}, B_{mD} or B_{mM} (where period of the structure $\leq T_0$)
≤ 2	0.8
5	1.0
10	1.2
20	1.5
30	1.8
40	2.1
50	2.4
60	2.7
70	3.0
80	3.3
90	3.6
≤ 100	4.0

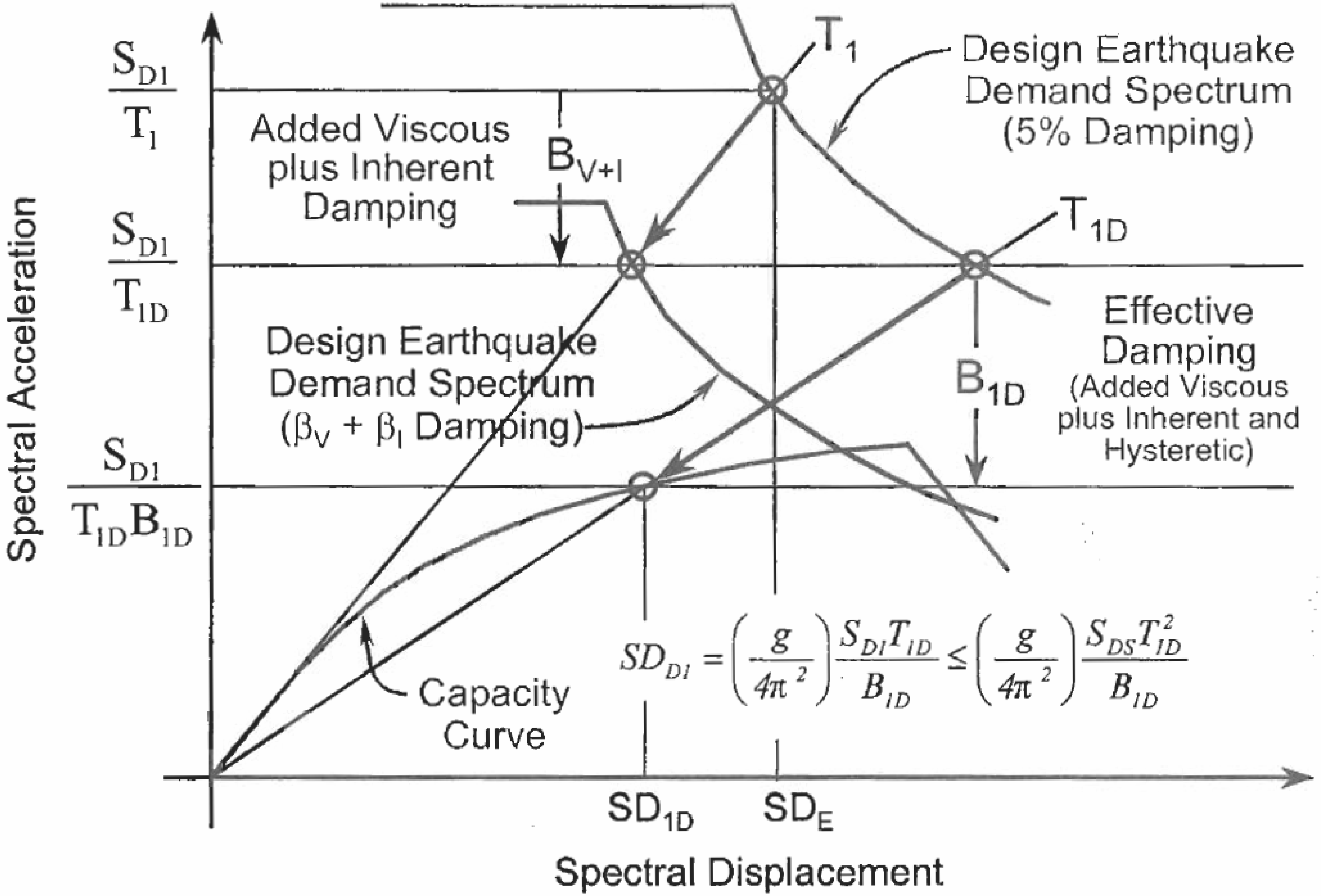


Figure C15-2. Effective damping reduction of design demand.

Types of Design Procedures

- Nonlinear procedures (static + dynamic)
  - Permitted for all structures with damping devices
- Response spectrum procedure
  - At least 2 dampers in each story
  - Effective damping in fundamental mode less than 35% of critical
- Equivalent lateral force procedure
  - At least 2 dampers in each story
  - Effective damping in fundamental mode less than 35% of critical
  - SFRS does not have plan irregularity
  - Rigid floor diaphragms
  - Height of the structure does not exceed 100 ft (30 m)

Equivalent Lateral Force Procedure (ELF)

- Response is defined by two modes:
  - The fundamental mode
  - The residual mode
    - New concept used to approximate the combined effects of higher modes that may be significant to story velocity

Equivalent Lateral Force Procedure (ELF)

- Seismic Base Shear for SFRS

$$\boxed{V = \sqrt{V_1^2 + V_R^2} \geq V_{\min}}$$

V_1 = Design base shear in fundamental mode
V_R = Design base shear in residual mode
V_{min} = Minimum design base shear

$$\boxed{V_{\min} = \frac{V}{B_{v+I}} \geq 0.75V}$$

B_{v+I} = Effective damping coefficient corresponding to the sum of viscous damping in fundamental mode + inherent damping in SFRS

Note: if SFRS has less than 2 dampers in any floor level or is irregular, $V_{min} = V$

Equivalent Lateral Force Procedure (ELF)

$$\boxed{V = \sqrt{V_1^2 + V_R^2} \geq V_{\min}}$$

- Fundamental Mode Base Shear

$$\boxed{V_1 = C_{S1} \overline{W}_1}$$

C_{S1} = Fundamental mode seismic response coefficient

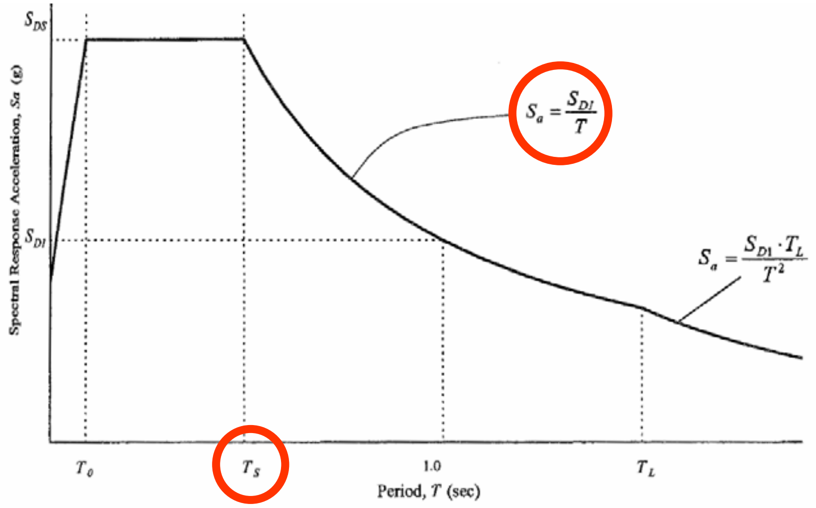
$\overline{W}_1$ = Fundamental modal weight (gravity load + portion of live load)

Equivalent Lateral Force Procedure (ELF)

$$\boxed{V_1 = C_{S1}\overline{W}_1}$$

- Fundamental Mode Seismic Response Coefficient

$$\boxed{\begin{aligned} &\text{For } T_{1D} < T_S,\ C_{S1} = \left(\frac{R}{C_d}\right)\frac{S_{D1}}{\Omega_o B_{1D}} \\ &\text{For } T_{1D} \geq T_S,\ C_{S1} = \left(\frac{R}{C_d}\right)\frac{S_{D1}}{T_{1D}\Omega_o B_{1D}} \end{aligned}}$$



T_{1D} = Effective fundamental period at the design displacement
R = Response modification coefficient associated with SFRS
Ω_o = Overstrength factor associated with SFRS
C_d = Deflection amplification factor
S_{DS} = Short period design spectral acceleration
S_{D1} = 1-second period design spectral acceleration
B_{1D} = Total effective first mode damping factor at the design displacement

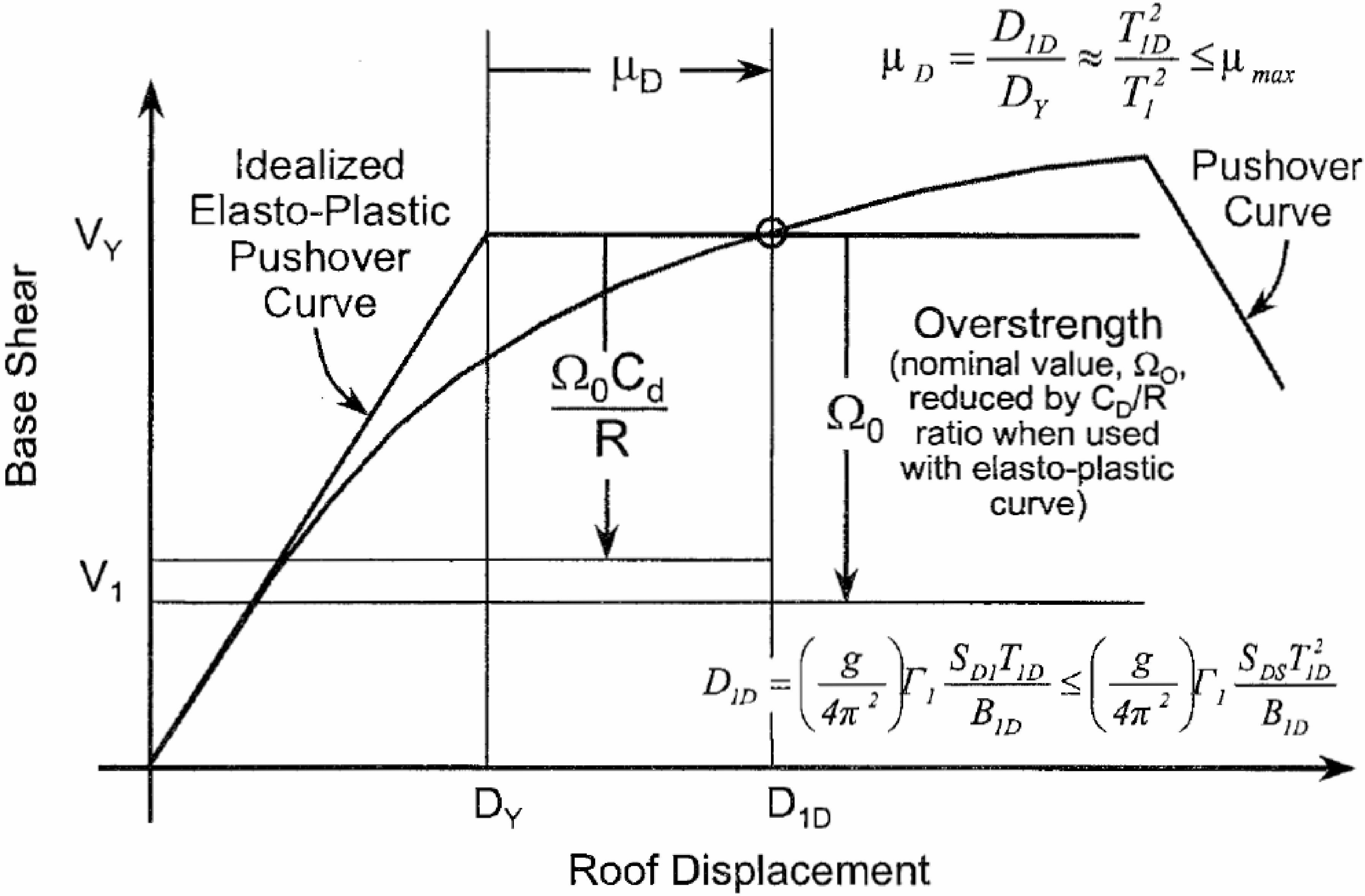


Figure C15-4. Idealized elasto-plastic pushover curve used for linear analysis.

Equivalent Lateral Force Procedure (ELF)

$$\text{For } T_{1D} < T_S,\ C_{S1} = \left(\frac{R}{C_d}\right)\frac{S_{D1}}{\Omega_o B_{1D}}$$

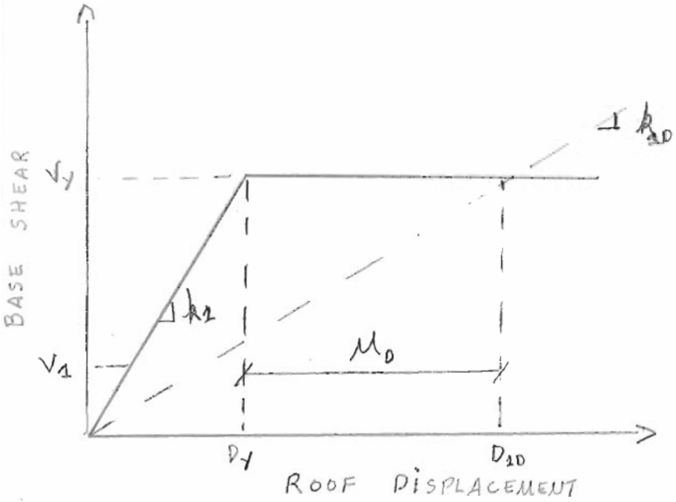
$$\text{For } T_{1D} \geq T_S,\ C_{S1} = \left(\frac{R}{C_d}\right)\frac{S_{D1}}{T_{1D}\Omega_o B_{1D}}$$

- Determination of Effective fundamental period

$$\boxed{T_{1D} = T_1\sqrt{\mu_D}}$$

T_1 = Fundamental period of SFRS

μ_D = Effective ductility demand of SFRS under DBE



$k_1 = \frac{V_y}{D_y}$; $k_{1D} = \frac{V_y}{D_{1D}}$

$\frac{k_1}{k_{1D}} = \left(\frac{T_{1D}}{T_1}\right)^2 = \frac{D_{1D}}{D_y} = \mu_D$

$\boxed{T_{1D} = T_1\sqrt{\mu_D}}$

Equivalent Lateral Force Procedure (ELF)

$$\boxed{T_{1D} = T_1\sqrt{\mu_D}}$$

- Determination of effective ductility demand at DBE

$$\boxed{\mu_D = \frac{D_{1D}}{D_Y}}$$

D_{1D} = Fundamental mode design displacement at center of rigidity of the roof level of the structure

D_Y = Displacement at the center of rigidity of the roof level of the structure at the effective yield point of the SFRS

Equivalent Lateral Force Procedure (ELF)

$$\mu_D = \frac{D_{1D}}{D_Y}$$

- Determination of fundamental mode design roof displacement

$$For\ T_{1D} < T_S\ ,\ D_{1D} = \left(\frac{g}{4\pi^2}\right)\Gamma_1 \frac{S_{DS}T_{1D}^2}{B_{1D}} \geq \left(\frac{g}{4\pi^2}\right)\Gamma_1 \frac{S_{DS}T_{1D}^2}{B_{1D}}$$

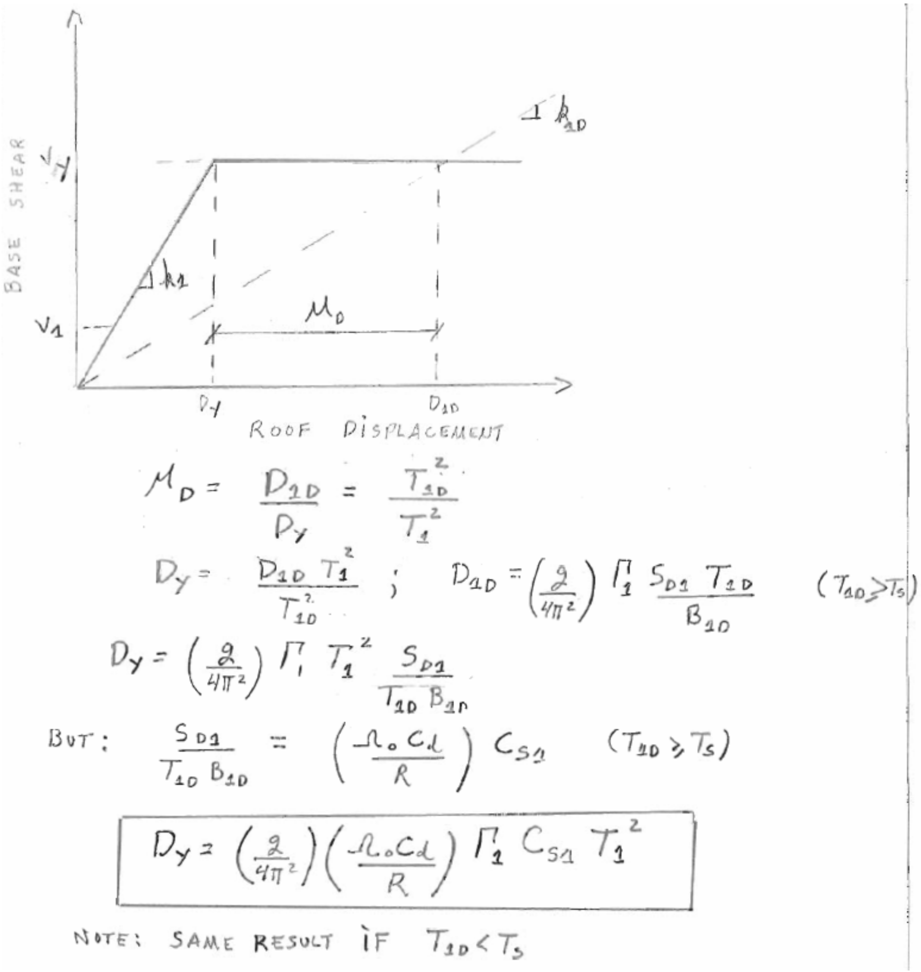
$$For\ T_{1D} \geq T_S\ ,\ D_{1D} = \left(\frac{g}{4\pi^2}\right)\Gamma_1 \frac{S_{D1}T_{1D}}{B_{1D}} \geq \left(\frac{g}{4\pi^2}\right)\Gamma_1 \frac{S_{D1}T_1}{B_{1E}}$$

Γ_1 = Fundamental mode participation factor
B_{1E} = Elastic First mode effective damping coefficient of SFRS

Equivalent Lateral Force Procedure (ELF)

$$\boxed{\mu_D = \frac{D_{1D}}{D_Y}}$$

- Determination of yield roof displacement



$$\mu_D = \frac{D_{1D}}{D_y} = \frac{T_{1D}^2}{T_1^2}$$

$$D_y = \frac{D_{1D}\,T_1^2}{T_{1D}^2} \;; \quad D_{1D} = \left(\frac{g}{4\pi^2}\right)\Gamma_1 \frac{S_{D1}\,T_{1D}}{B_{1D}} \qquad (T_{1D} \geq T_s)$$

$$D_y = \left(\frac{g}{4\pi^2}\right)\Gamma_1\, T_1^2\, \frac{S_{D1}}{T_{1D}\,B_{1D}}$$

BUT: $\frac{S_{D1}}{T_{1D}\,B_{1D}} = \left(\frac{\Omega_o C_d}{R}\right) C_{S1} \qquad (T_{1D} \geq T_s)$

$$\boxed{D_y = \left(\frac{g}{4\pi^2}\right)\left(\frac{\Omega_o C_d}{R}\right)\Gamma_1\, C_{S1}\, T_1^2}$$

NOTE: SAME RESULT IF $T_{1D} < T_s$

$$\boxed{D_Y = \left(\frac{g}{4\pi^2}\right)\left(\frac{\Omega_o C_d}{R}\right)\Gamma_1 C_{s1} T_1^2}$$

Equivalent Lateral Force Procedure (ELF)

$$\boxed{V = \sqrt{V_1^2 + V_R^2} \geq V_{\min}}$$

- Residual Mode Base Shear

$$\boxed{V_R = C_{SR}\overline{W_R}}$$

C_{SR} = Residual mode seismic response coefficient

$\overline{W_R}$ = Residual modal weight

$$\boxed{\overline{W_R} = W - \overline{W_1}}$$

Equivalent Lateral Force Procedure (ELF)

$$\boxed{V_R = C_{SR}\overline{W}_R}$$

- Residual Mode Seismic Response Coefficient

$$\boxed{C_{SR} = \left(\frac{R}{C_d}\right)\frac{S_{DS}}{\Omega_o B_R}}$$

B_R = Total effective residual mode damping factor

Equivalent Lateral Force Procedure (ELF)

- Design lateral forces of SFRS

$$F_i = \sqrt{F_{i1}^2 + F_{iR}^2}$$

$$F_{i1} = w_i \phi_{i1} \frac{\Gamma_1}{\overline{W}_1} V_1$$

$$F_{iR} = w_i \phi_{iR} \frac{\Gamma_R}{\overline{W}_R} V_R$$

F_i = Design lateral force at level i
F_{i1} = First Mode Design lateral force at level i
F_{iR} = Residual Mode Design lateral force at level i
w_i = Seismic weight at level I
ϕ_{i1} = Amplitude of fundamental mode shape at level i
ϕ_{i1} = Amplitude of residual mode shape at level I
Γ_1 = First mode participation factor
Γ_R = Residual mode participation factor

Equivalent Lateral Force Procedure (ELF)

$$F_{i1} = w_i \phi_{i1} \frac{\Gamma_1}{\overline{W}_1} V_1$$

$$F_{iR} = w_i \phi_{iR} \frac{\Gamma_R}{\overline{W}_R} V_R$$

- Modal properties

$$\phi_{i1} = \frac{h_i}{h_r} \; ; \; \phi_{iR} = \frac{1 - \Gamma_1 \phi_{i1}}{1 - \Gamma_1} \; ; \; \Gamma_1 = \frac{\overline{W}_1}{\sum_{i=1}^{n} w_i \phi_{i1}} \; ; \; \overline{W}_1 = \frac{\left(\sum_{i=1}^{n} w_i \phi_{i1} \right)^2}{\sum_{i=1}^{n} w_i \phi_{i1}^2}$$

$$\Gamma_R = 1 - \Gamma_1 \; ; \; \overline{W}_R = W - \overline{W}_1$$

$$T_R = 0.4 T_1$$

Computation of Effective Damping

$$\boxed{\begin{aligned}\beta_{mD} &= \beta_I + \beta_{Vm}\sqrt{\mu_D} + \beta_{HD} \\ \beta_{mM} &= \beta_I + \beta_{Vm}\sqrt{\mu_M} + \beta_{HM}\end{aligned}}$$

β_{mD}, β_{mM} = Effective damping in mth mode of vibration at design displacement and maximum displacement, respectively

β_I = Inherent damping of SFRS at or just below yield < 5% of critical for all modes

β_{Vm} = Damping provided by viscous dampers at or just below yield of SFRS

β_{HD}, β_{HM} = Damping provided by hysteretic dampers and SFRS at design displacement and maximum displacement, respectively

μ_M = Effective ductility demand of SFRS under MCE

Computation of Effective Damping

$$\beta_{mD} = \beta_I + \beta_{Vm}\sqrt{\mu_D} + \beta_{HD}$$

$$\beta_{mM} = \beta_I + \beta_{Vm}\sqrt{\mu_M} + \beta_{HM}$$

- Hysteretic Damping

$$\beta_{HD} = q_H\left(0.64 - \beta_I\right)\left(1 - \frac{1}{\mu_D}\right)$$

$$\beta_{HM} = q_H\left(0.64 - \beta_I\right)\left(1 - \frac{1}{\mu_M}\right)$$

$$q_H = 0.67\frac{T_S}{T_1}$$

Computation of Effective Damping

- Determination of effective ductility demand at MCE

$$\boxed{\mu_M = \frac{D_{1M}}{D_Y}}$$

D_{1M} = Fundamental mode maximum displacement at center of rigidity of the roof level of the structure

D_Y = Displacement at the center of rigidity of the roof level of the structure at the effective yield point of the SFRS

Equivalent Lateral Force Procedure (ELF)

$$\boxed{\mu_M = \frac{D_{1M}}{D_Y}}$$

- Determination of fundamental mode maximum roof displacement

$$\boxed{\begin{aligned} &For\ T_{1M} < T_S\ ,\ D_{1M} = \left(\frac{g}{4\pi^2}\right)\Gamma_1 \frac{S_{MS}T_{1M}^2}{B_{1M}} \geq \left(\frac{g}{4\pi^2}\right)\Gamma_1 \frac{S_{MS}T_{1M}^2}{B_{1M}} \\ &For\ T_{1M} \geq T_S\ ,\ D_{1M} = \left(\frac{g}{4\pi^2}\right)\Gamma_1 \frac{S_{M1}T_{1M}}{B_{1M}} \geq \left(\frac{g}{4\pi^2}\right)\Gamma_1 \frac{S_{M1}T_1}{B_{1E}} \end{aligned}}$$

Computation of Effective Damping

- Viscous Damping

$$\boxed{\beta_{Vm} = \frac{\sum_j W_{mj}}{2\pi \sum_i F_{im}\delta_{im}}}$$

W_{mj} = Energy dissipated per cycle of jth viscous damper in mth mode of vibration at displacement δ_{im}

δ_{im} = Deflection of Level i in mth mode of vibration corresponding to yield level of SFRS

F_{im} = mth mode inertial force at Level i

Design of Damping Devices

- Design forces in damping devices and other elements of damping systems must be determined on the basis of story drifts and story velocities at DBE

Design of Damping Devices

- Design interstory drift at DBE

$$\boxed{\Delta_D = \sqrt{\Delta_{1D}^2 + \Delta_{1R}^2}}$$

Δ_{1D} = First mode story drift at DBE
Δ_{1R} = *Residual* mode story drift at DBE

Design of Damping Devices

- Design story velocity at DBE

$$\boxed{v_D = \sqrt{v_{1D}^2 + v_{1R}^2}}$$

v_{1D} = First mode story velocity at DBE
v_{1R} = *Residual* mode story velocity at DBE

$$\boxed{\begin{gathered} v_{1D} = 2\pi \frac{\Delta_{1D}}{T_{1D}} \\ v_{1R} = 2\pi \frac{\Delta_{1R}}{T_{1R}} \end{gathered}}$$

Design Steps

1. Calculate minimum base shear, V_{min}
2. Develop trial design of SFRS for V_{min}
3. Establish first and residual modal properties
4. Select target first mode supplemental damping value (β_{v1}) to meet drift limits as if SFRS responds elastically
5. Assume trial value of μ_D (in the range of 1.5 to 2.0) calculate β_{1D} and T_{1D}
6. Calculate B_{1D}, C_{S1} and V_1
7. If V_1 is approximately equal to V_{min}, proceed to step 8, otherwise revise value of μ_D in step 5

Design Steps

8. Calculate D_Y, D_{1D}, and μ_D
9. Calculate B_R, C_{SR} and V_R
10. Calculate design base shear V and design lateral forces
11. Design dampers for design interstory drifts and velocities.
12. Verify components of SFRS under maximum forces generated by dampers (maximum displacement, velocity and acceleration)

Testing Requirements

- Prototype testing
  - Two full-size dampers of each type
  - Wind tests (if applicable)
  - 5 fully reversed sinusoidal cycles at MCE displacement and at frequency $1/T_{1M}$
  - *3 different temperatures (minimum, ambient, and maximum) if dampers are temperature-sensitive*
  - *15% changes allowed in fore-displacement properties*

Testing Requirements

- Production testing
  - All dampers to be installed
  - Verify force-velocity-displacement characteristics
  - Protocol to be determined by engineer-in-record

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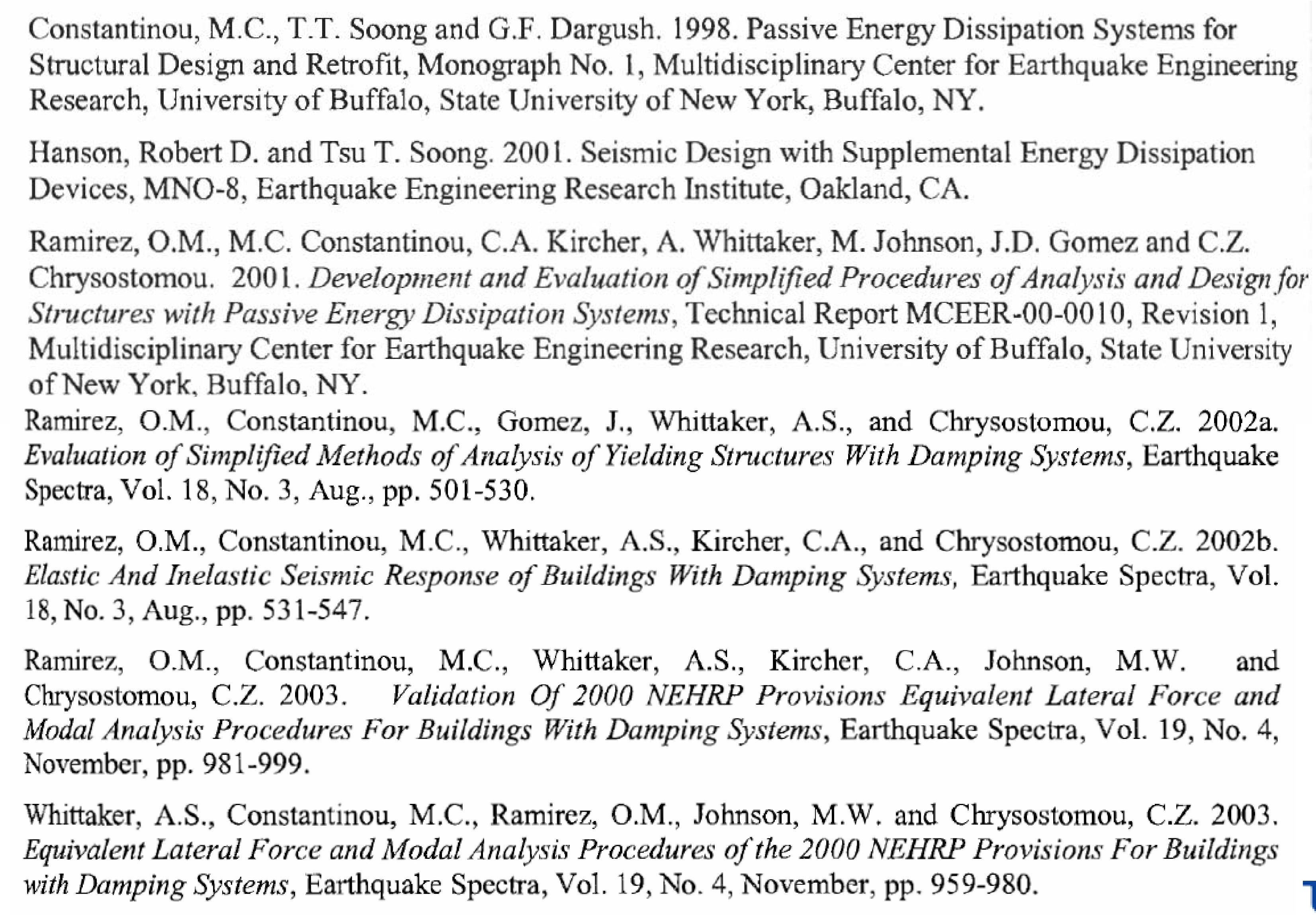

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