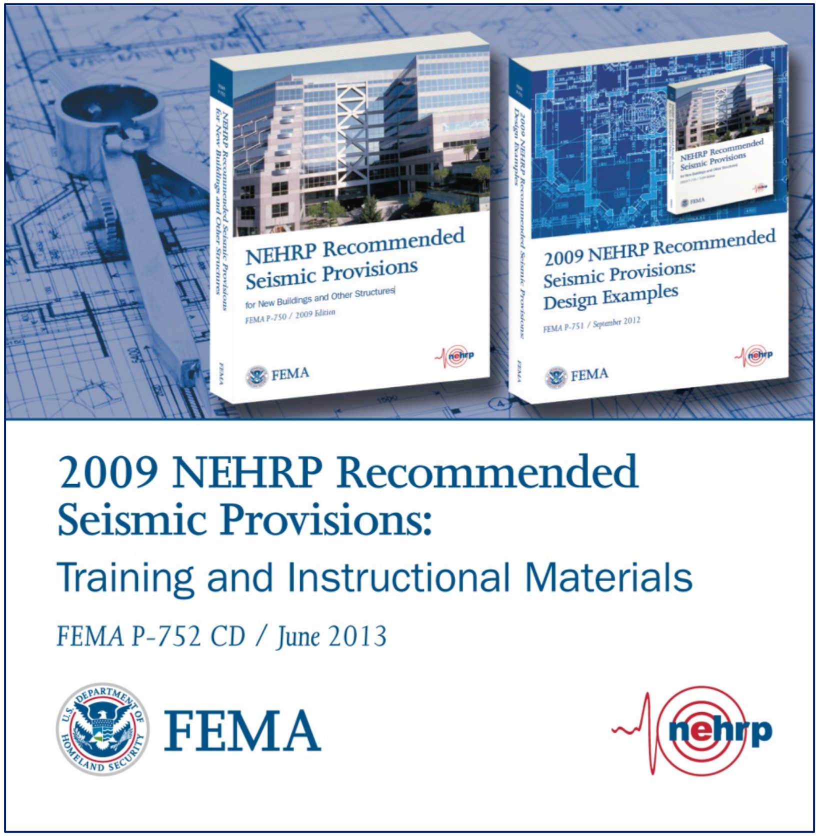


12

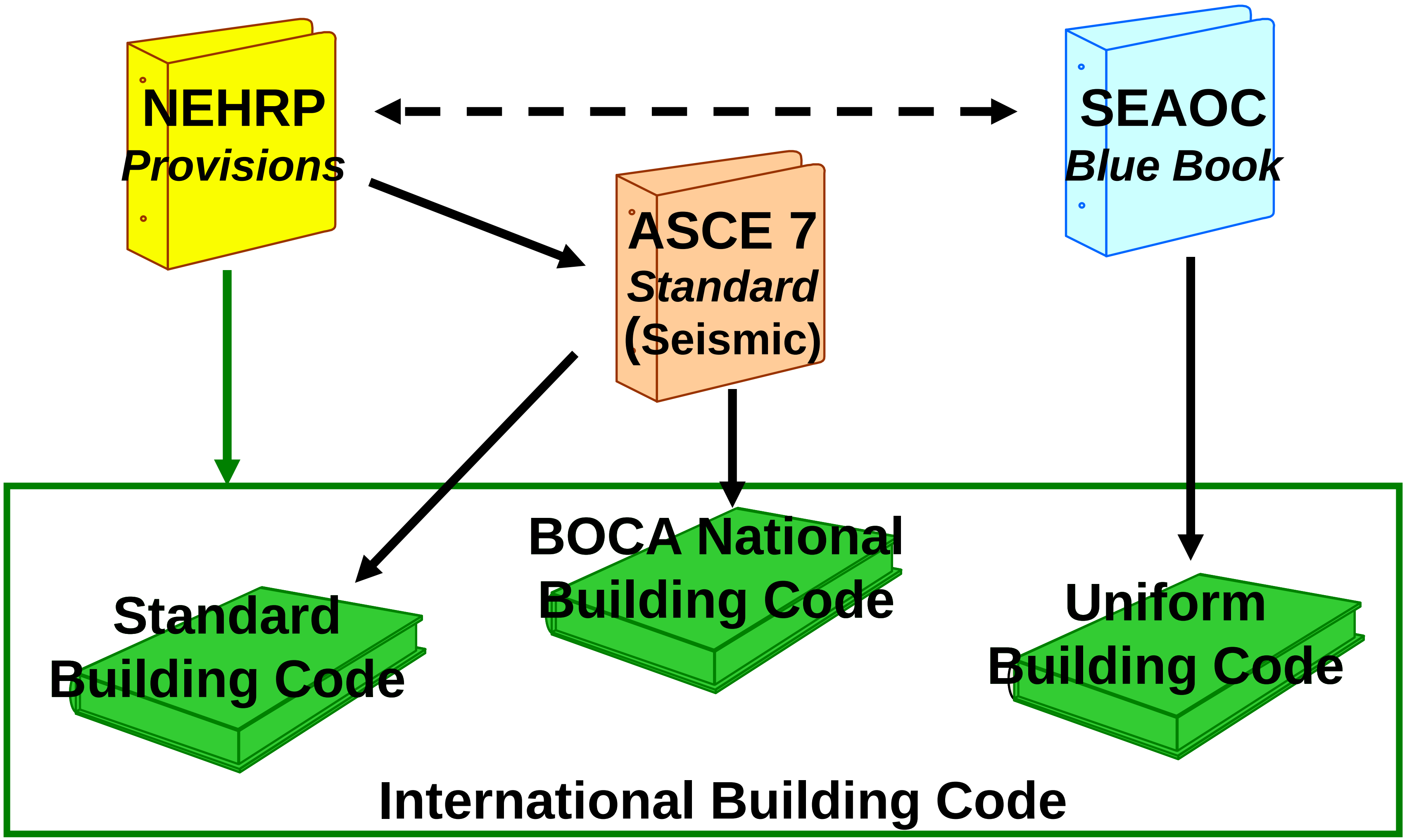
Seismically Isolated Structures

Charles A. Kircher, P.E., Ph.D.

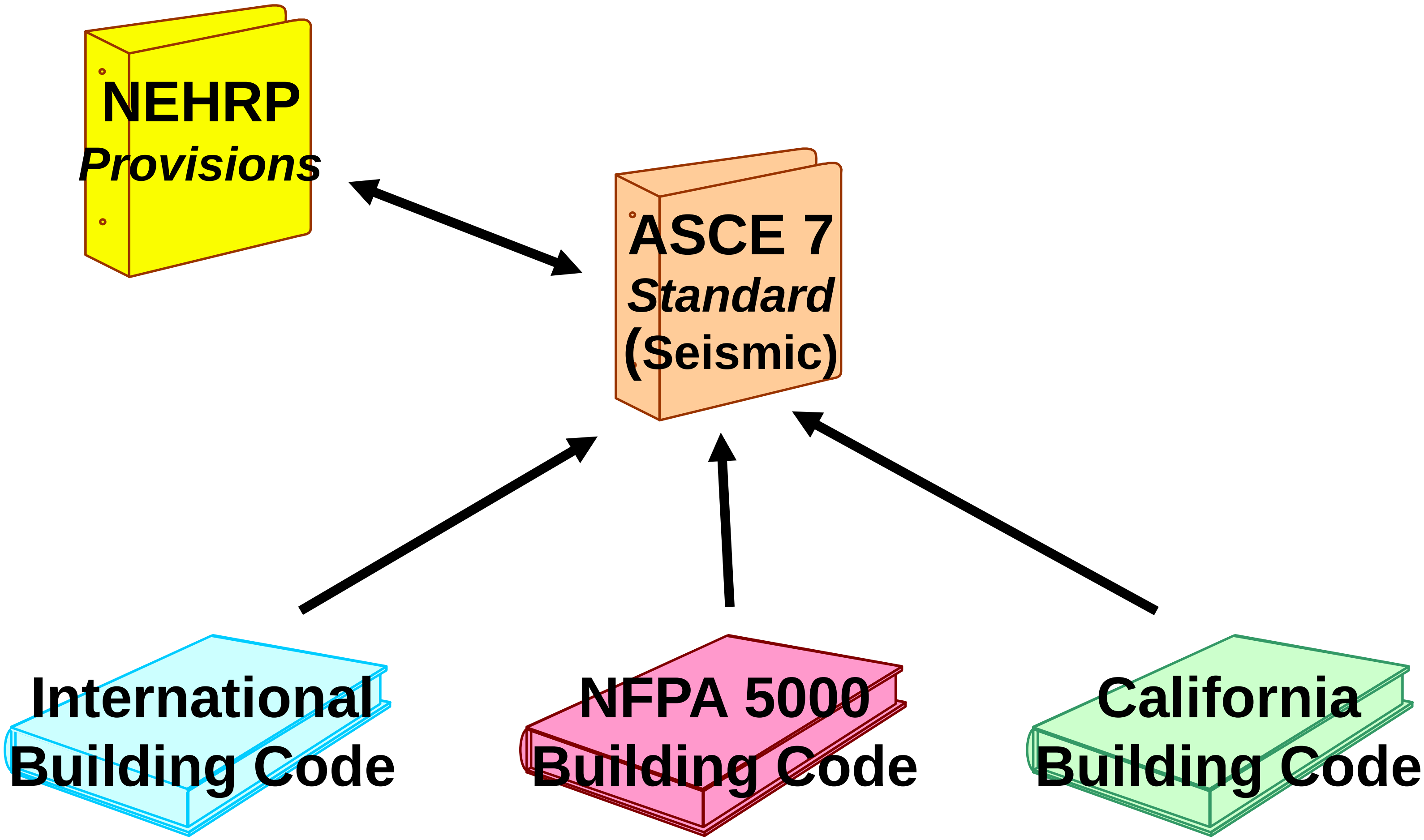
Presentation Objectives

- Present background material and basic concepts of seismic isolation
- Review seismic-code design requirements:
  - Chapter 17 – ASCE Standard ASCE/SEI 7-05, Minimum Design Loads for Buildings and Other Structures (referred to as the *Standard*)
- Illustrate typical application with a design example of seismically isolated structure
  - Hypothetical three-story emergency operation center (EOC) located in a region of high seismicity

Background and Basic Concepts
Seismic Codes/Source Documents - Past



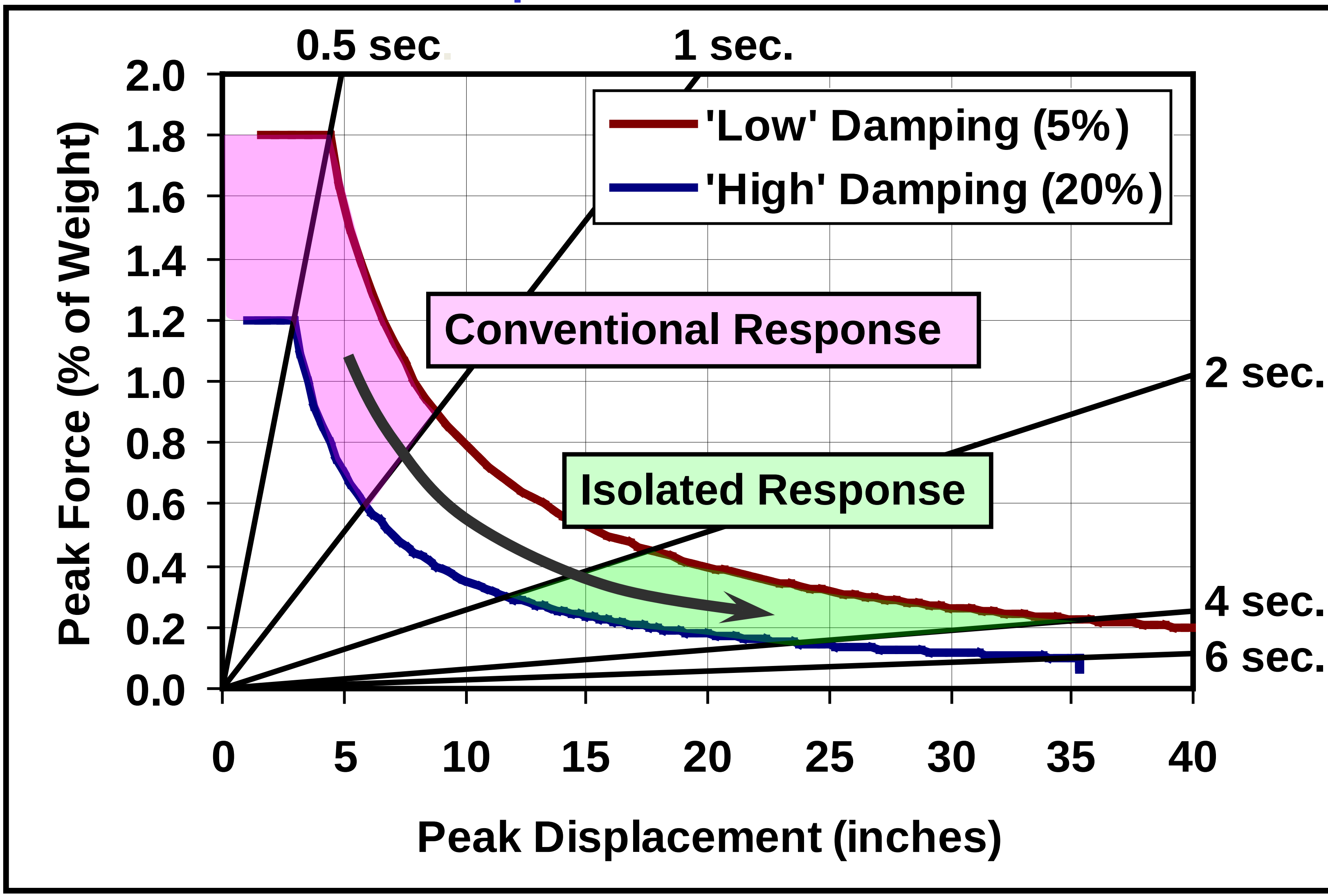
Background and Basic Concepts
Seismic Codes/Source Documents - Current



Background and Basic Concepts
Earthquake Response Modification

- De-couple structure above the isolation interface from potential damaging earthquake ground motions
- De-couple structure from earthquake ground motions by increasing period of the isolated structure to several times the period of the same structure on a fixed base
  - Trade displacement (of the isolation system) for force (in the structure above the isolation system)

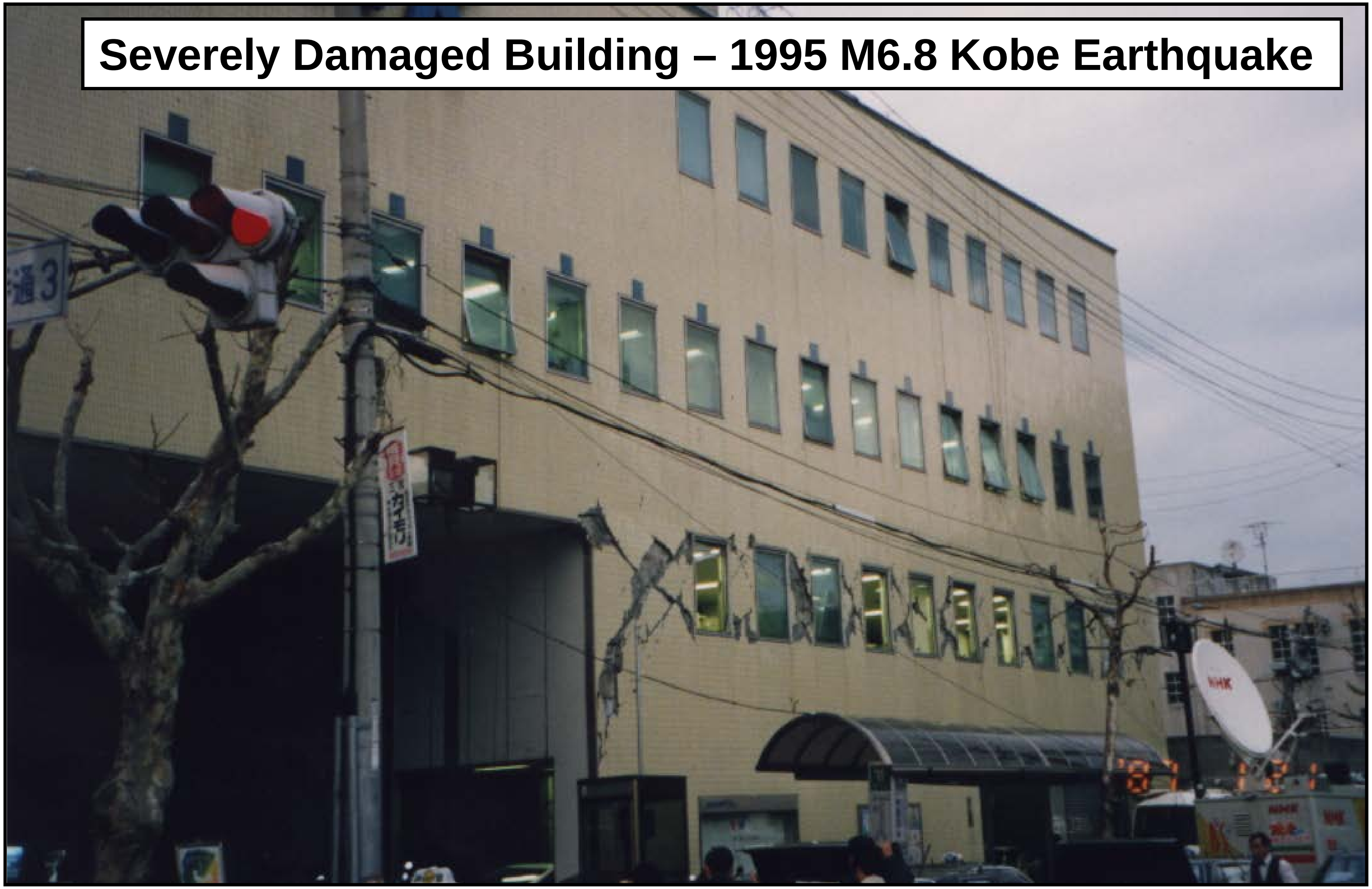
Background and Basic Concepts
Trade Displacement for Force



Example – Map of ASCE 7-10 Ground Motions

1-Second MCE_R Spectral Acceleration (Site Class D)

Background and Basic Concepts
Video of Earthquake Shaking



Severely Damaged Building – 1995 M6.8 Kobe Earthquake

Background and Basic Concepts
Seismic-Code Performance Objectives
(Section 1.1, 2009 *NEHRP Provisions*)

- Intent of these Provisions is to provide reasonable assurance of seismic performance:
  - Avoid serious injury and life loss
  - Avoid loss of function in critical facilities
  - Minimize nonstructural repair costs (where practical to do so)
- Objectives addressed by:
  - Avoiding structural collapse in very rare, extreme ground shaking
  - Limiting damage to structural and nonstructural systems that could lead to injury, economic loss or loss of functions for smaller more frequent ground motions

Background and Basic Concepts
Seismic-Code Performance Objectives
(Table C17.2-1 , 2009 *NEHRP Provisions*)

Performance Measure		Earthquake Ground Motion Intensity Level		
Type	Description	Minor	Moderate	Major
Life Safety	Loss of life or serious injury is not expected	**F, I**	**F, I**	**F, I**
Structural Damage	Significant structural damage is not expected	**F, I**	**F, I**	**I**
Nonstructural Damage	Significant nonstructural or contents damage is not expected	**F, I**	**I**	**I**

F indicates fixed-base structures; **I** indicates isolated structures

Background and Basic Concepts
Seismic-Code Performance Objectives
(Implicit for seismically isolated structures)

- Intent of these Provisions is to provide reasonable assurance of seismic performance:
  - Avoid serious injury and life loss
  - Avoid loss of function in ~~critical~~ all facilities
  - Minimize structural, nonstructural and contents repair costs
- Objectives addressed by:
  - Avoiding structural collapse in very rare, extreme ground shaking
  - Avoiding ~~Limiting~~ damage to structural and nonstructural systems and contents that could lead to injury, economic loss or loss of functions for smaller more frequent ground motions by reducing earthquake demands on these systems

Background and Basic Concepts
Seismic Isolation Applications – New Buildings

- Motivating Factors
  - Maintain functionality
  - Protect contents
  - Avoid economic loss
- Typical Applications
  - Hospitals
  - Emergency operations centers
  - Other critical facilities (Risk Category IV)
  - Research facilities (laboratories)
  - Hi-tech manufacturing facilities
  - Art museums

Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Background and Basic Concepts

Example Protection of Contents (and Function)

New de Young Museum – San Francisco

Delicate Glass Sculpture - *Nijima and Ikehana* Boats
“Chihuly at the de Young” (2008)

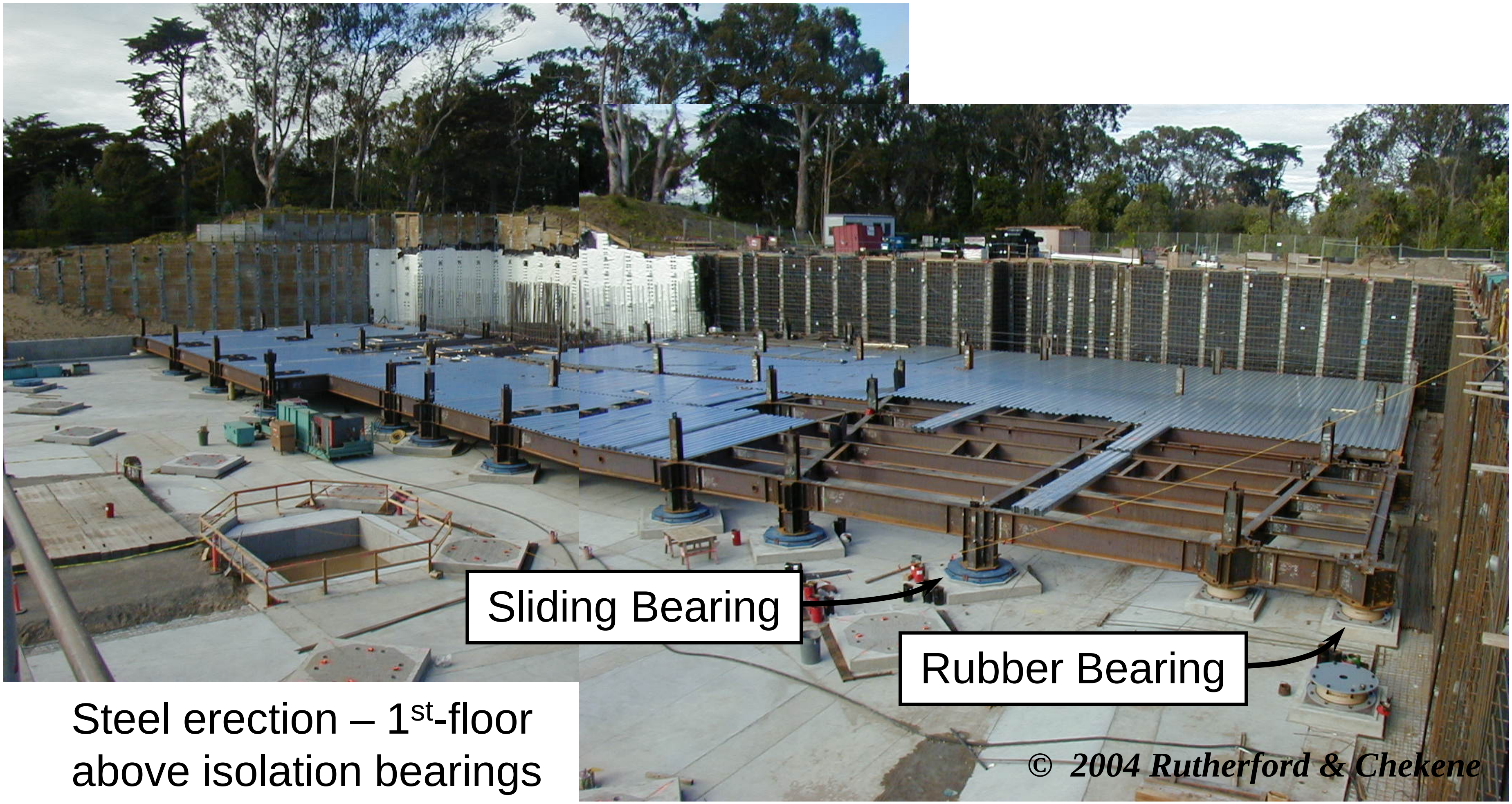
Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Grade beams and crane Installation

Background and Basic Concepts

Example Protection of Contents (and Function)

New de Young Museum – San Francisco



Steel erection – 1st-floor above isolation bearings

Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Steel erection – upper floors

Example Protection of Contents (and Function)

New de Young Museum – San Francisco

Crawl space - rubber bearings on pedestals

Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Crawl space – sliding bearing and supplementary fluid viscous damper

Background and Basic Concepts
Isolation System Terminology

- Isolation System

"The collection of structural elements that includes all individual isolator units, all structural elements that transfer force between elements of the isolation system, and all connections to other structural elements. The isolation system also includes the wind-restraint system, energy-dissipation devices, and/or the displacement restraint system if such systems and devices are used to meet the design requirements of this chapter."

Background and Basic Concepts
Isolation System Terminology

- Isolator Units

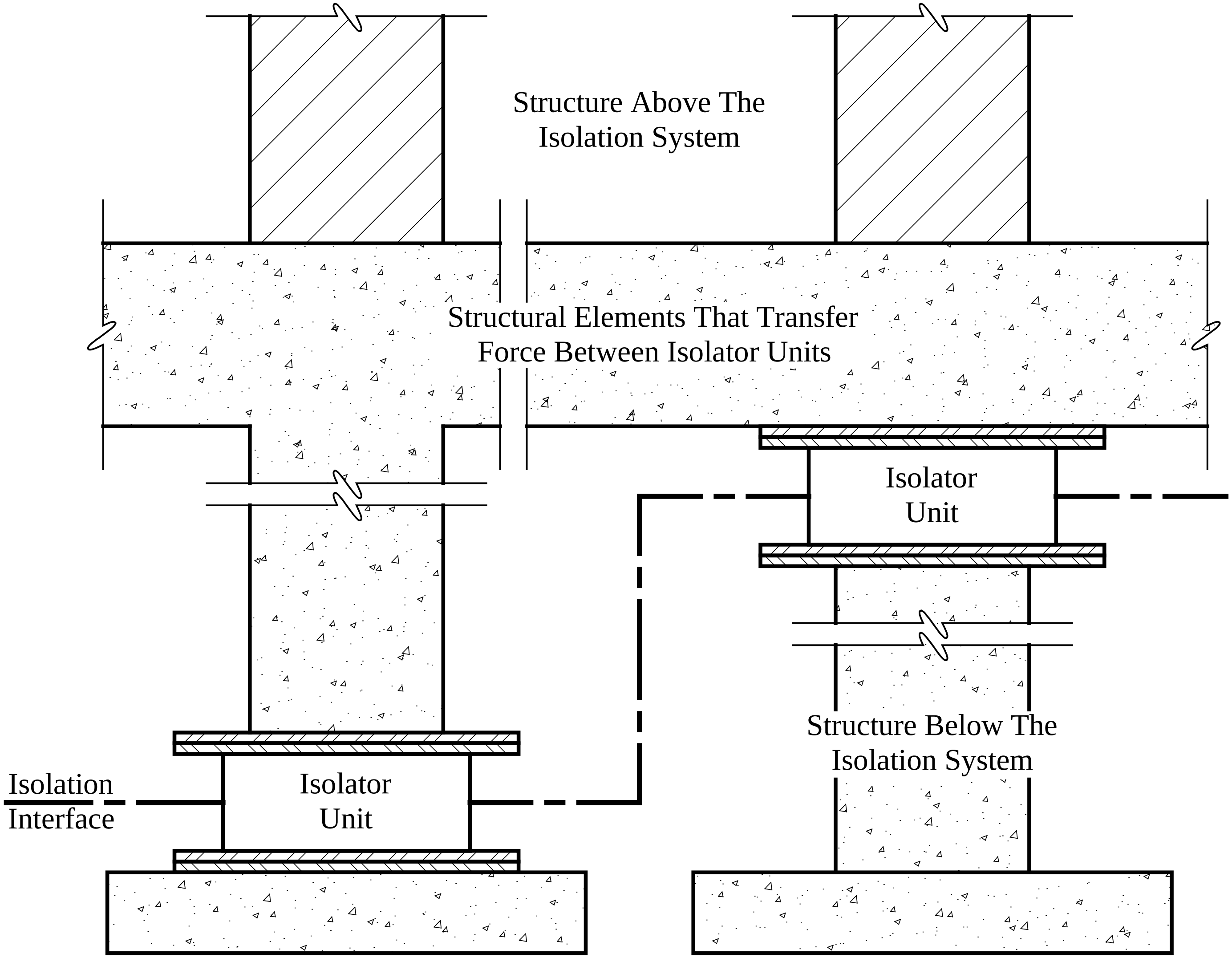
  "A horizontally flexible and vertically stiff element of the isolation system that permits large lateral deformations under design seismic load. An isolator unit is permitted to be used either as part of, or in addition to, the weight-supporting system of the structure."

- Isolation Interface

  "The boundary between the upper portion of the structure, which is isolated, and the lower portion of the structure, which moves rigidly with the ground."

Background and Basic Concepts

Isolation System Terminology



Isolation Products Used in the United States

- Elastomeric (rubber) Isolators
  - High-damping rubber (HDR) bearings
  - Lead-rubber (LR) bearings
- Sliding Isolators
  - Friction pendulum system (FPS)
    - Single-concave sliding surface bearings
    - Double-concave sliding surface bearings
    - Triple-pendulum bearings
  - Flat sliding bearings (used with rubber isolators)
- Supplementary Dampers
  - Fluid-viscous dampers

Background and Basic Concepts
Acceptable Isolation Systems

- The *Standard* permits the use of any type of isolation system or product provided that the system/isolators:
  - Remain stable for maximum earthquake displacements
  - Provide increasing resistance with increasing displacement
  - Have limited degradation under repeated cycles of earthquake load
  - Have well-established and repeatable engineering properties (effective stiffness and damping)
- The *Standard* does not preclude, but does not fully address 3-D isolation systems that isolate the structure in the vertical, as well as the horizontal direction

Background and Basic Concepts
General Design Requirements – Isolation System

- The *Standard* (Section 17.2.4) prescribes general design requirements for the isolation system regarding:
  - Environmental Conditions
  - Wind Forces
  - Fire Resistance
  - Lateral Restoring Force
  - Displacement Restraint
  - Vertical-load Stability
  - Overturning
  - Inspection and Replacement
  - Quality Control

Background and Basic Concepts
General Design Requirements – Structural System and Nonstructural Components

- The *Standard* (Section 17.2.5) prescribes general design requirements for the structural system regarding:
  - Horizontal Distribution of Force
  - Building Separations
  - Nonbuilding Structures
- The *Standard* (Section 17.2.6) prescribes general design requirements for nonstructural components regarding:
  - Components at or above the Isolation Interface
  - Components Crossing the Isolation Interface
  - Components below the Isolation Interface

Criteria Selection
Acceptable Methods of Analysis*

Site Conditions or Structure Configuration Criteria	ELF Procedure	Response Spectrum	Time History
Site Conditions			
Near-Source ($S_1 \geq 0.6$)	NP	P	P
Soft soil (Site Class E or F)	NP	NP	P
Superstructure Configuration			
Flexible or irregular superstructure (h > 4 stories, h > 65 ft., or $T_M > 3.0$ s, or $T_D \leq 3T$)**	NP	P	P
Nonlinear superstructure (requiring explicit modeling of nonlinear elements, Sec. 17.6.2.2.1)	NP	NP	P
Isolation System Configuration			
Highly nonlinear isolation system or does not meet the criteria of Section 17.4.1, Item 7	NP	NP	P

* P indicates permitted and NP indicates not permitted by the *Standard*

** T is the elastic, fixed-base, period of the structure above the isolation system

Background and Basic Concepts
Design Approach

- Design the structure above the isolation system for forces associated with design earthquake ground motions, reduced by only a fraction of the factor permitted for design of conventional, fixed-base buildings (R_I = 3/8R ≤ 2.0)
- Design the isolation system and the structure below the isolation system (e.g., the foundation) for unreduced design earthquake forces (R_I = 1.0)
- Design and prototype test isolator units for forces (including effects of overturning) and displacements associated with the maximum considered earthquake (MCE_R) ground motions
- Provide sufficient separation between the isolated structure and surrounding retaining walls and other fixed obstructions to allow unrestricted movement during MCE_R ground motions

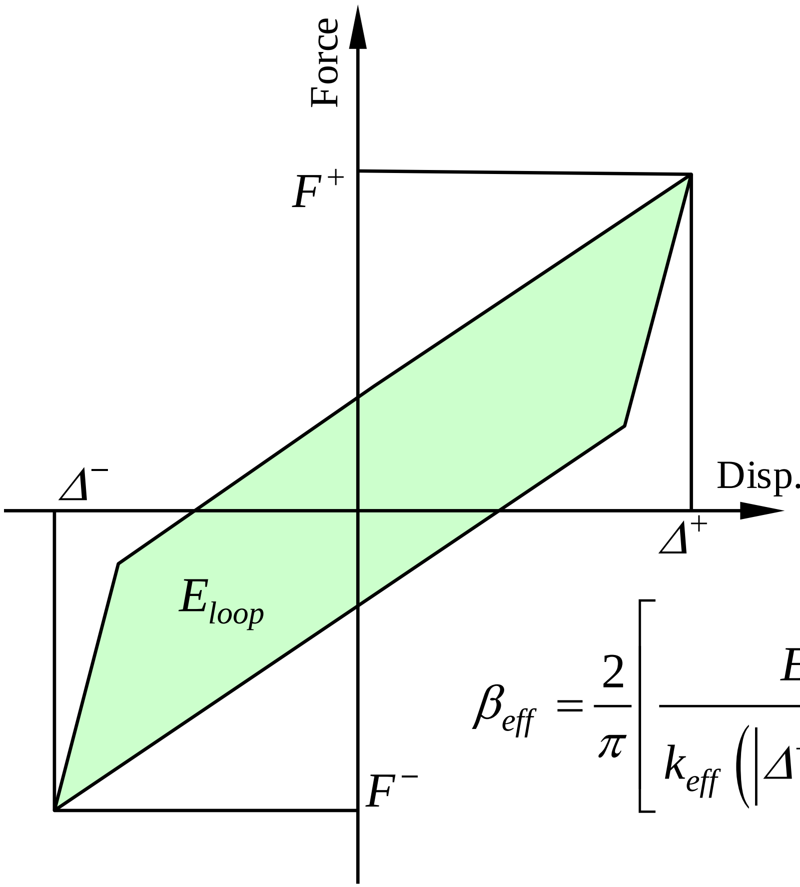
Background and Basic Concepts
Design Approach

- Design the structure above the isolation system, the isolation system, and the structure below the isolation system (e.g., the foundation) for more critical of loads based on bounding values of isolation system force-deflection properties:
  - Design the isolation system for displacements based on minimum effective stiffness of the isolation system
  - Design the structure above for forces based on maximum effective stiffness of the isolation system
- Variations in Material Properties (Section 17.1.1):

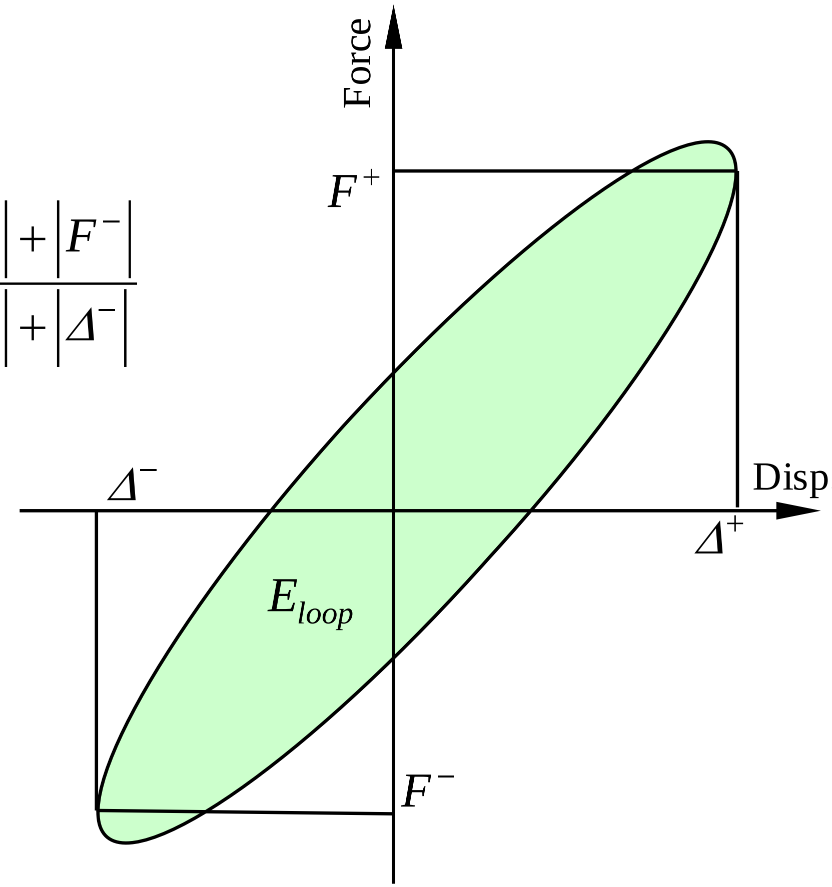
"The analysis of seismically isolated structures, including the substructure, isolators, and superstructure, shall consider variations in seismic isolator material properties including changes due to aging, contamination, environmental exposure, loading rate, scragging and temperature."

Background and Basic Concepts
Effective Stiffness and Damping

Hysteretic Isolator



Viscous Isolator



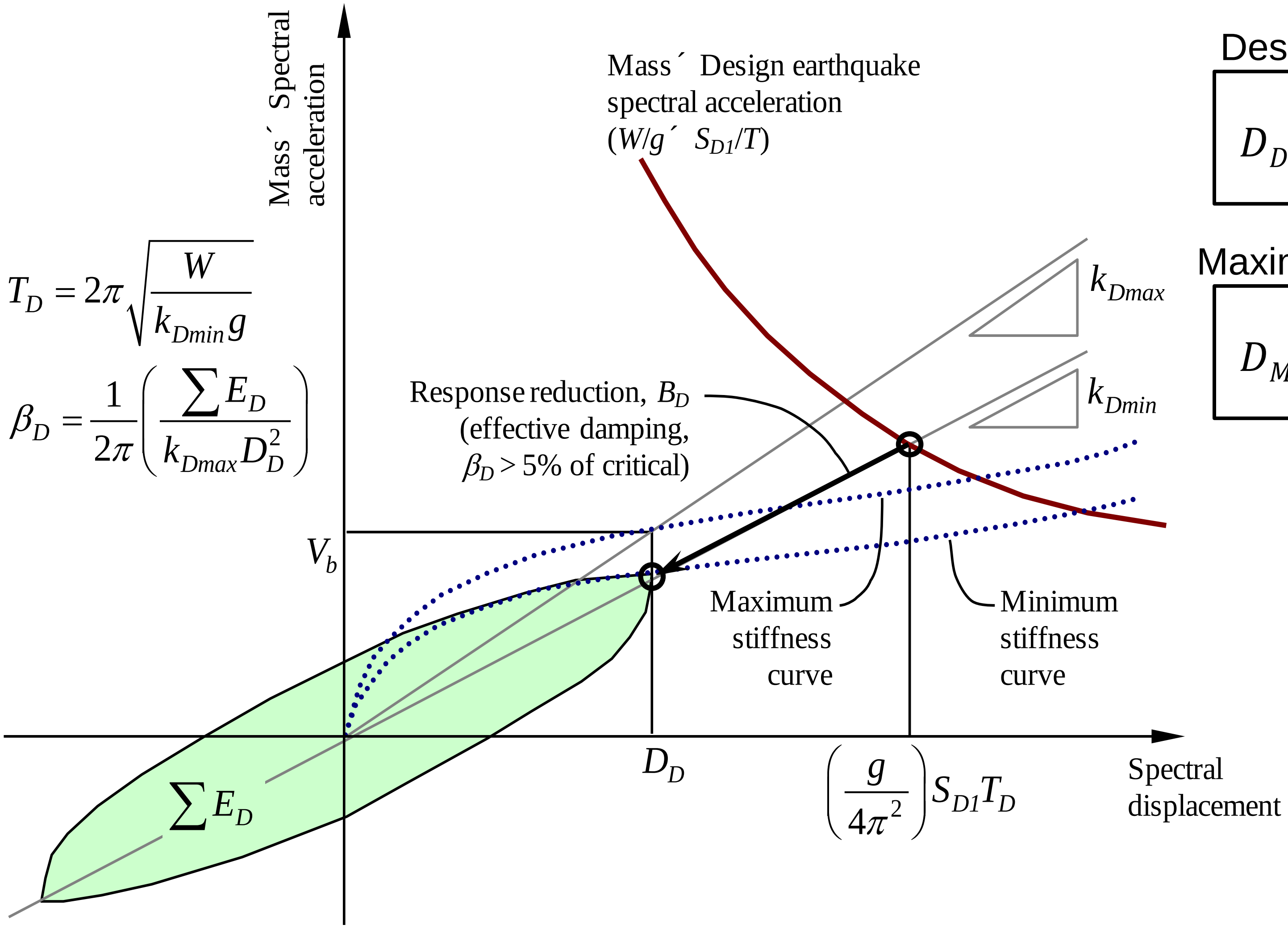
$$k_{eff} = \frac{\left|F^+\right| + \left|F^-\right|}{\left|\Delta^+\right| + \left|\Delta^-\right|}$$

$$\beta_{eff} = \frac{2}{\pi}\left[\frac{E_{loop}}{k_{eff}\left(\left|\Delta^+\right| + \left|\Delta^-\right|\right)^2}\right]$$

Equivalent Lateral Force Procedure
Isolation System Displacement (D_D and D_M)

$$T_D = 2\pi\sqrt{\frac{W}{k_{Dmin}g}}$$

$$\beta_D = \frac{1}{2\pi}\left(\frac{\sum E_D}{k_{Dmax}D_D^2}\right)$$



Design Displacement

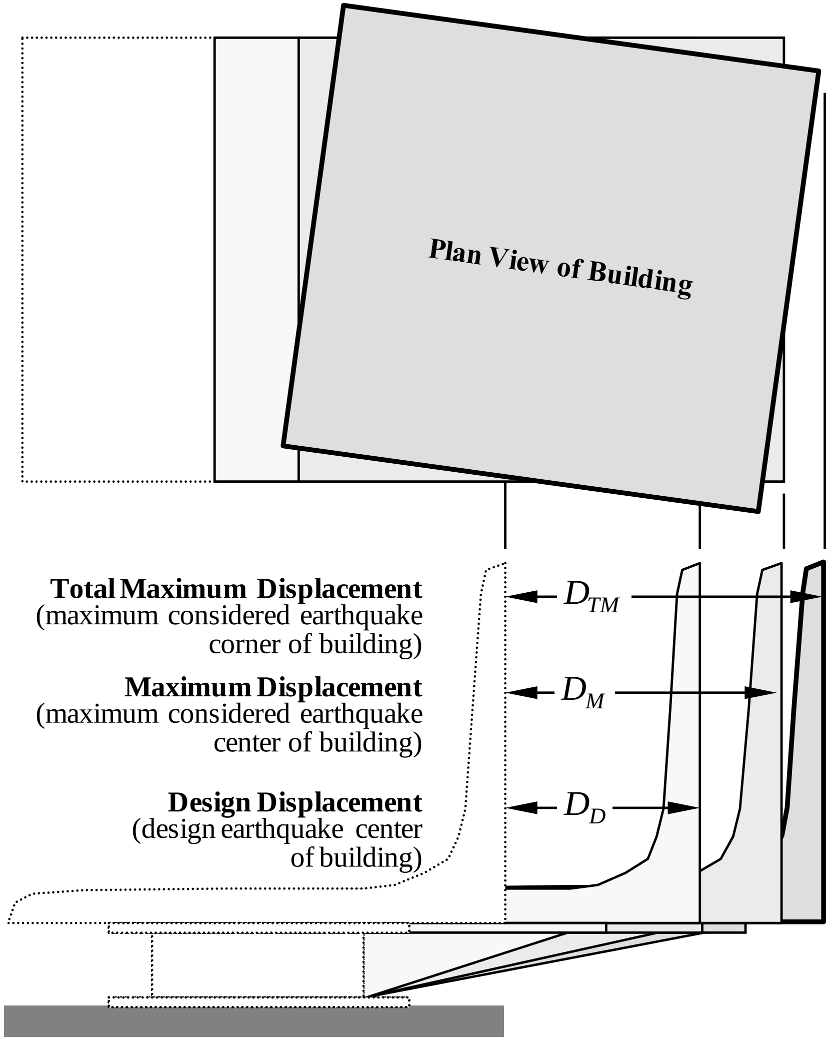
$$D_D = \left(\frac{g}{4\pi^2}\right)\frac{S_{D1}T_D}{B_D}$$

Maximum Displacement

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

B_D, B_M	β_D, β_M
0.8	≤ 2%
1.0	5%
1.2	10%
1.35	15%
1.5	20%
1.7	30%
1.9	40%
2.0	≥ 50%

Equivalent Lateral Force Procedure
Total Maximum Displacement (D_{TD} and D_{TM})



Total Design Displacement

$$D_{TD} = D_D \left[1 + y \frac{12e}{b^2 + d^2}\right]$$

Total Maximum Displacement

$$D_{TM} = D_M \left[1 + y \frac{12e}{b^2 + d^2}\right]$$

Where:

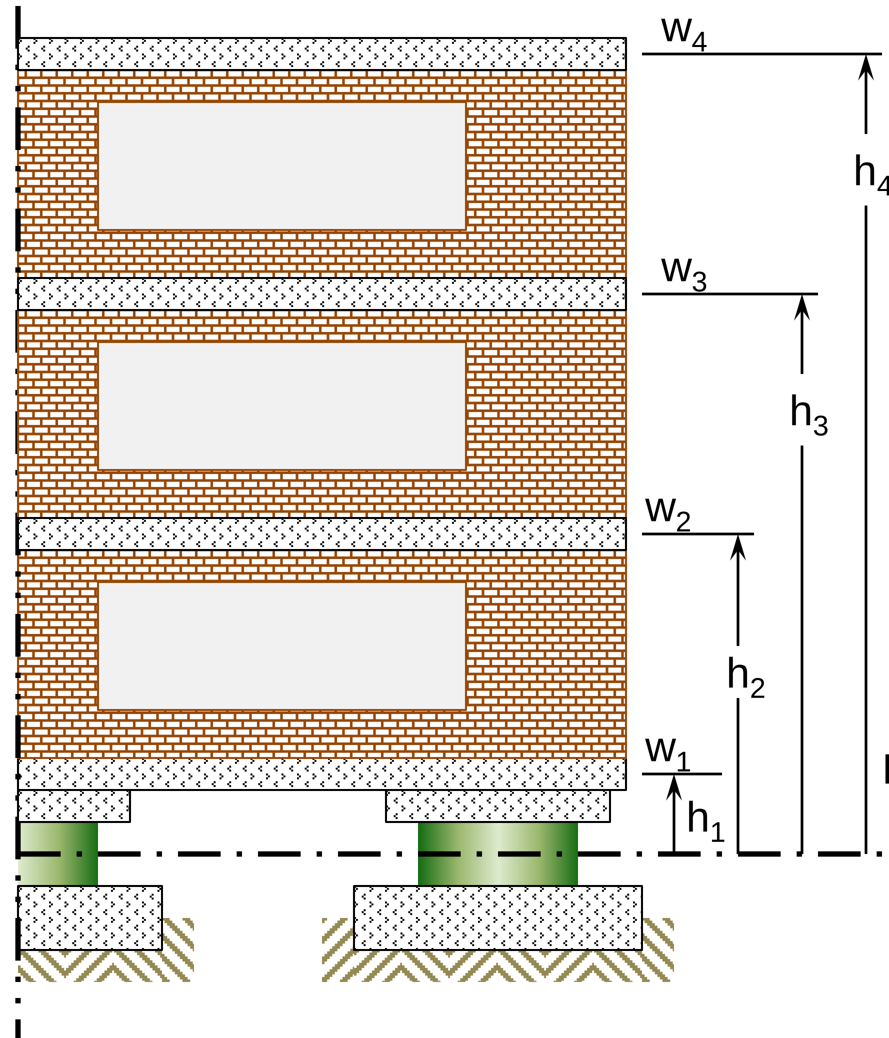
y = distance in plan from center of rigidity to corner

e = actual plus accidental eccentricity (i.e., 0.05d)

b = shortest plan dimension

d = longest plan dimension

Equivalent Lateral Force Procedure
Design Forces (V_b, V_s and F_x)



Design Shear Force at Level x

$$F_x = \frac{V_s w_x h_x}{\sum_i w_i h_i}$$

Design Shear – Isolated Structure

$$V_s = \frac{V_b}{R_I} = \frac{k_{Dmax} D_D}{R_I}$$

V_s must be at least as large as:

(1) Fixed-base design shear force ($T = T_D$)

(2) Wind design shear force

(3) 1.5 times shear force required to activate the Isolation system

Design Shear – Isolation System/Structure below

$$V_b = k_{Dmax} D_D$$

Isolation Level

Equivalent Lateral Force Procedure
Response Modification Factor (R_I)

- Response modification factor (R_I) required for design of the structure above the isolation system is limited to:

$$R_I = \frac{3}{8}R \leq 2$$

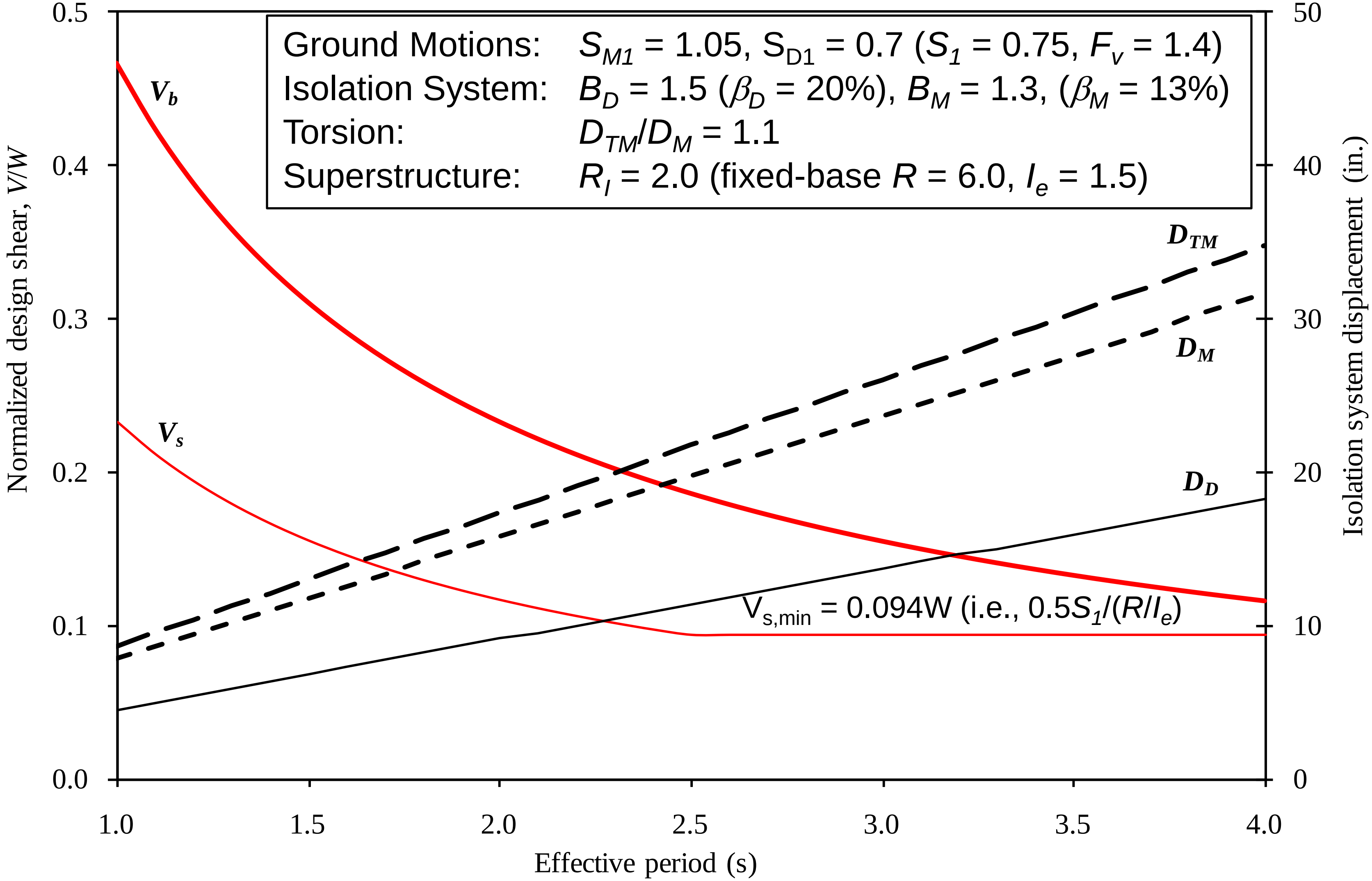
- Example values of R_I for high-seismic SDC D, E and F structures:

Seismic Force Resisting System	***Standard***		***IBC***	
	Fixed Base (R)	Isolated (R_I)	Fixed Base (R)	Isolated (R_I)
Steel Ordinary Concentric Brace Frames	3¼[1]	1.2	3¼[1]	1.0[2]
Steel Special Concentric Braced Frames	6	2	6	2
Steel Ordinary Moment Frames	NP	NP	NP	1.0[2]
Steel Special Moment Frames	8	2	8	2

1. Limited to 35 feet (SDC D and E); NP in SDC F
2. 2006 IBC permits steel OCBFs and steel OMFs designed for R_I = 1.0 and AISC 341

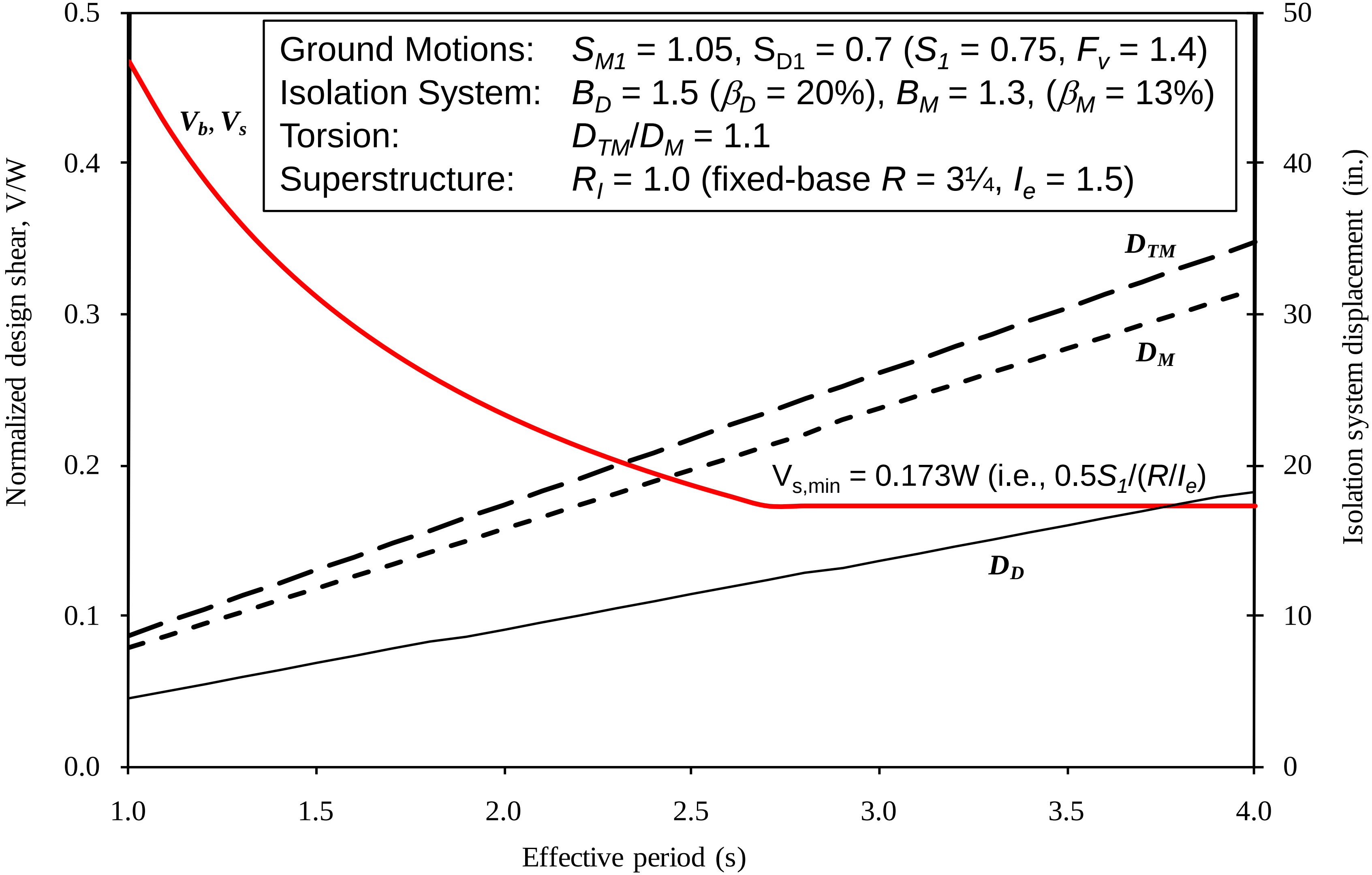
Equivalent Lateral Force Procedure

Example Values of Design Parameters (Steel SCBF)



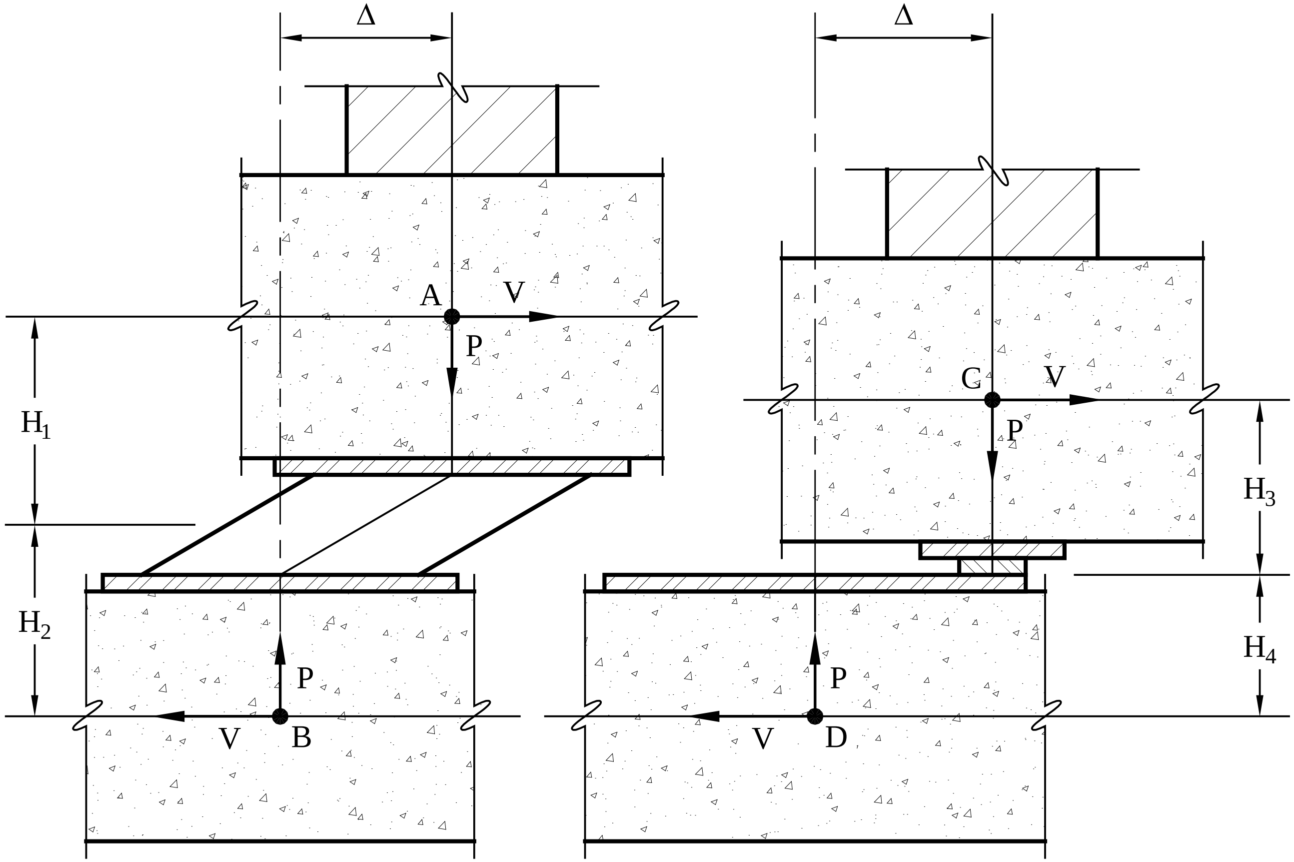
Equivalent Lateral Force Procedure

Example Values of Design Parameters (Steel OCBF)



Modeling and Analysis

Moments due to P-Delta Effects (and horizontal shear)



$M_A = VH_1 + P\Delta/2$

$M_B = VH_2 + P\Delta/2$

$M_C = VH_3$

$M_D = VH_4 + P\Delta$

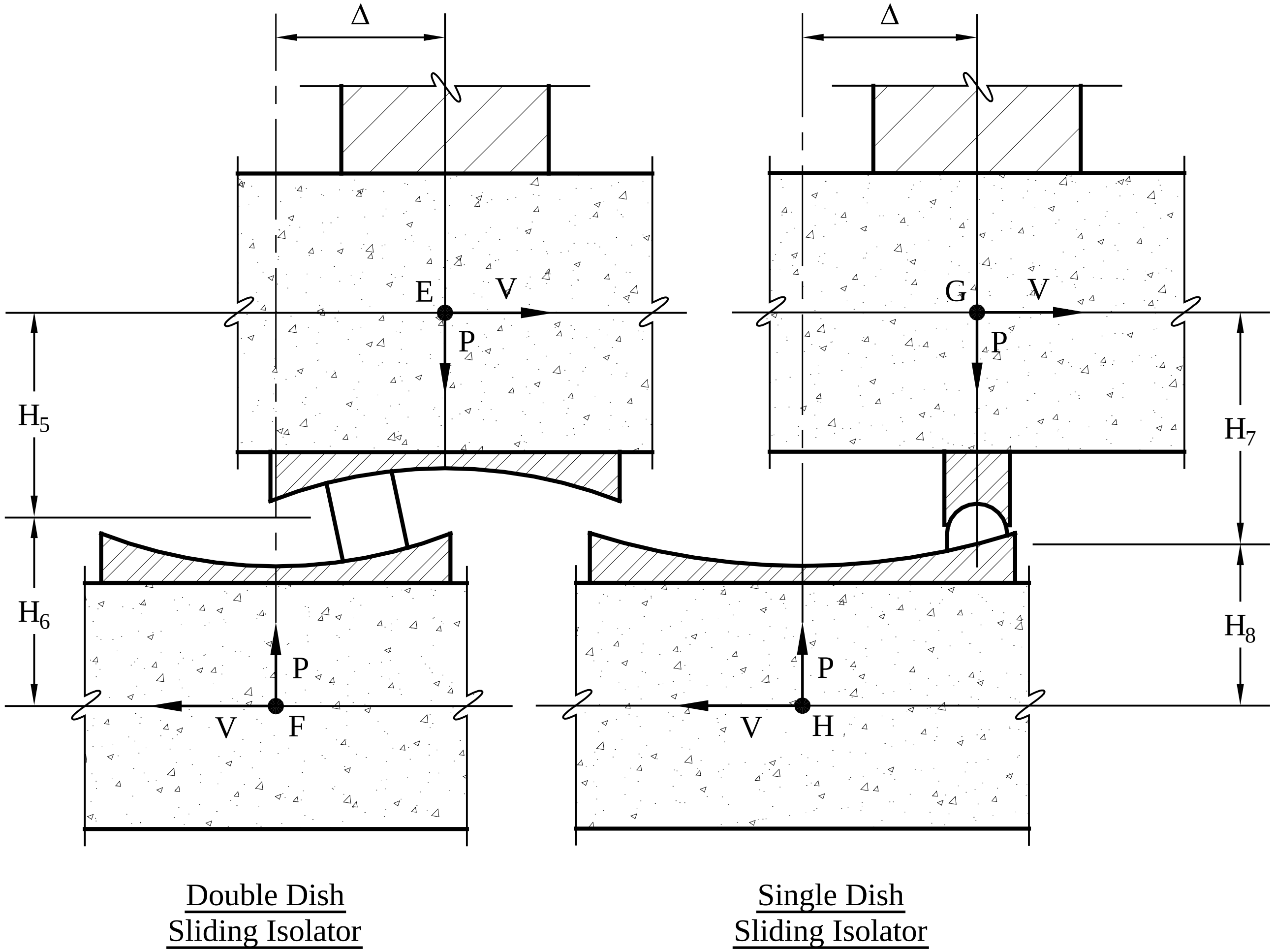
Elastomeric Isolator

Flat Sliding Isolator

Moments due to P-Delta Effects (and horizontal shear)

$M_E = VH_5 + P\Delta/2$

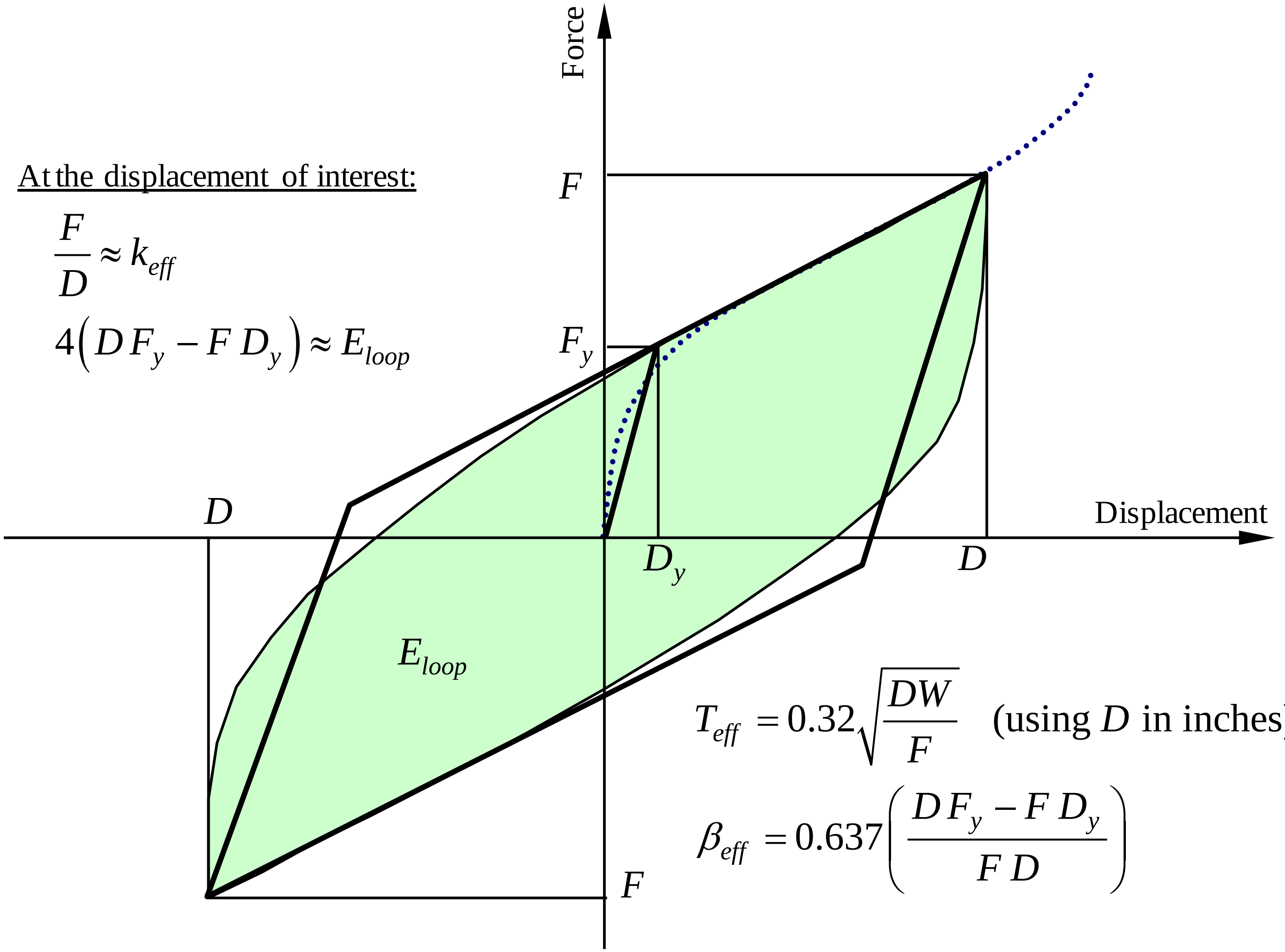
$M_F = VH_6 + P\Delta/2$



$M_G = VH_7$

$M_H = VH_8 + P\Delta$

Modeling and Analysis
Bilinear Idealization of Isolator Unit Behavior



At the displacement of interest:

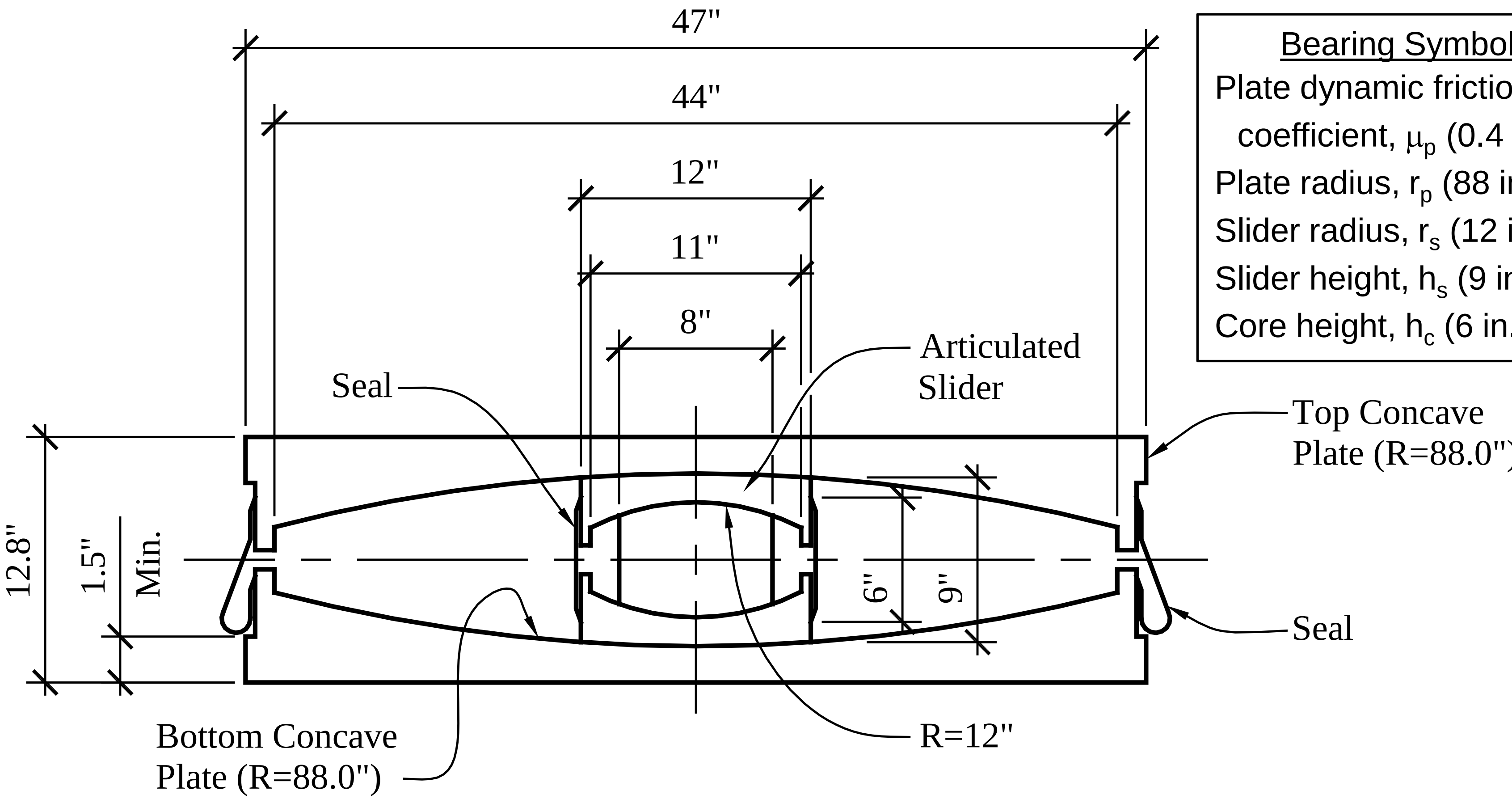
$$\frac{F}{D} \approx k_{eff}$$

$$4\left(D\,F_y - F\,D_y\right) \approx E_{loop}$$

$$T_{eff} = 0.32\sqrt{\frac{DW}{F}} \quad \text{(using } D \text{ in inches)}$$

$$\beta_{eff} = 0.637\left(\frac{D\,F_y - F\,D_y}{F\,D}\right)$$

Bilinear Idealization of Double-Concave FPS Bearing

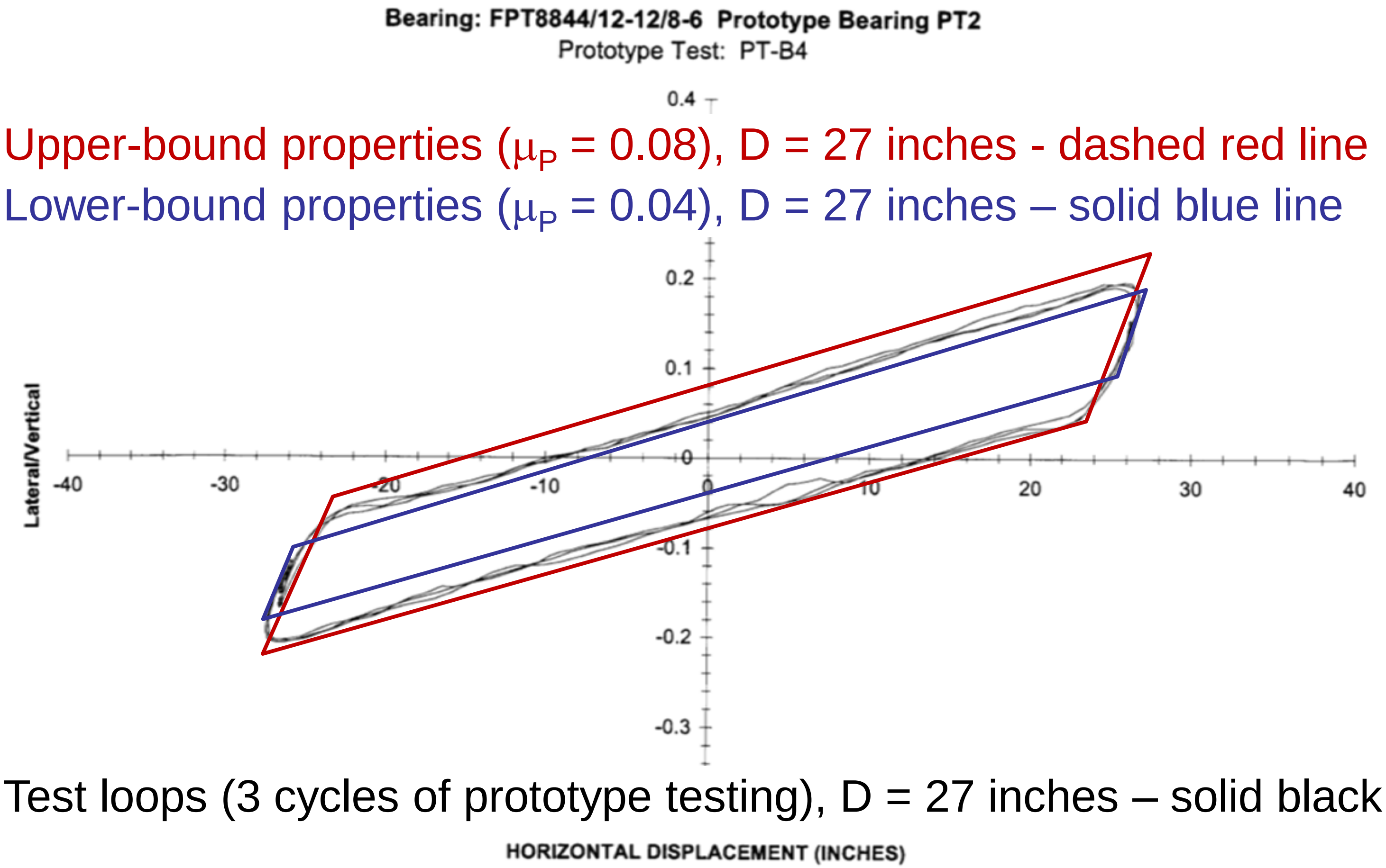


Bearing Symbols

- Plate dynamic friction coefficient, μ_p (0.4 - 0.8)
- Plate radius, r_p (88 in.)
- Slider radius, r_s (12 in.)
- Slider height, h_s (9 in.)
- Core height, h_c (6 in.)

Section view of the double-concave friction pendulum bearing FPT8844/12-12/8-6)

Modeling and Analysis
Comparison of Modeled and Tested Hysteresis Loops



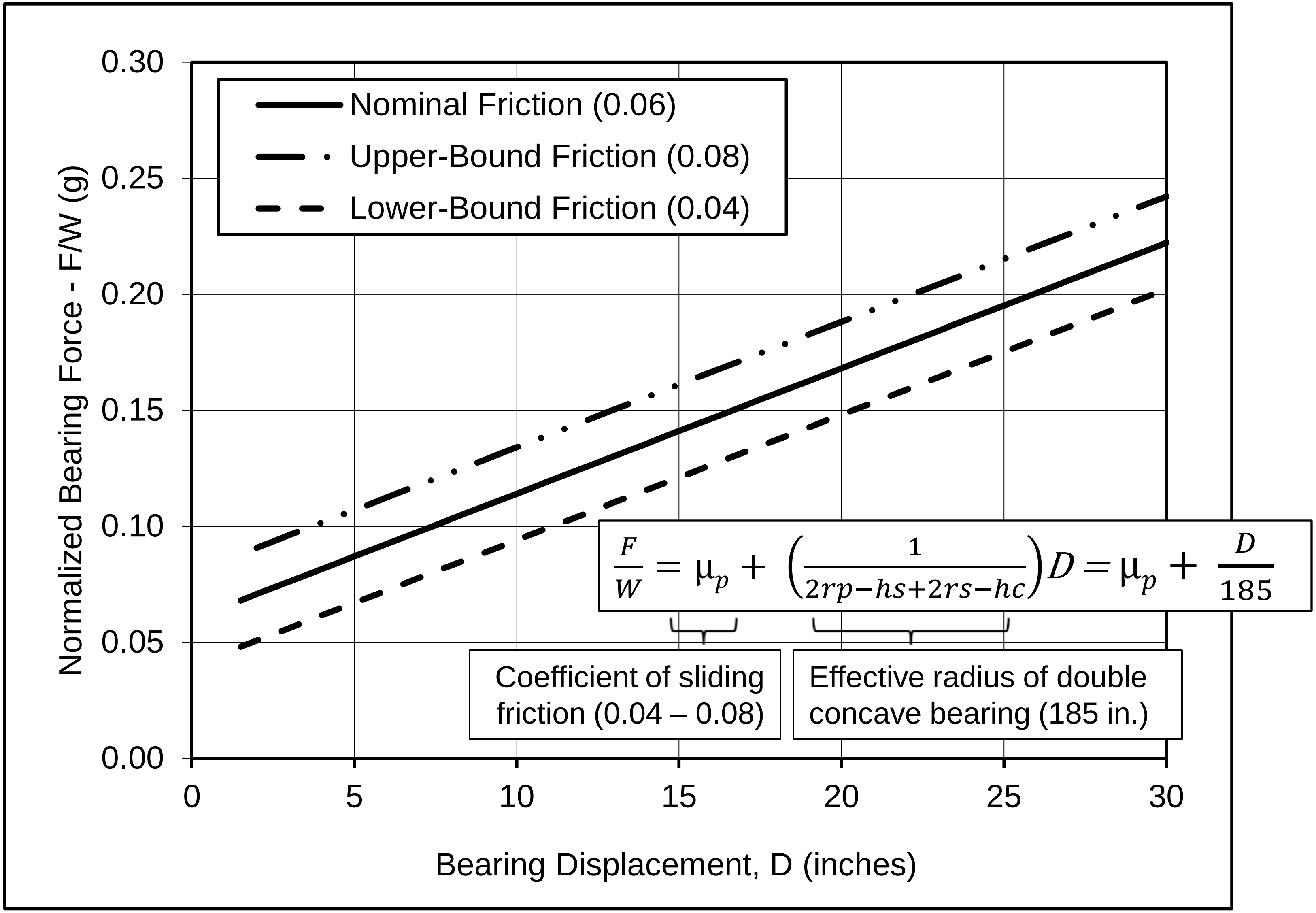
Upper-bound properties (μ_P = 0.08), D = 27 inches - dashed red line

Lower-bound properties (μ_P = 0.04), D = 27 inches – solid blue line

Test loops (3 cycles of prototype testing), D = 27 inches – solid black

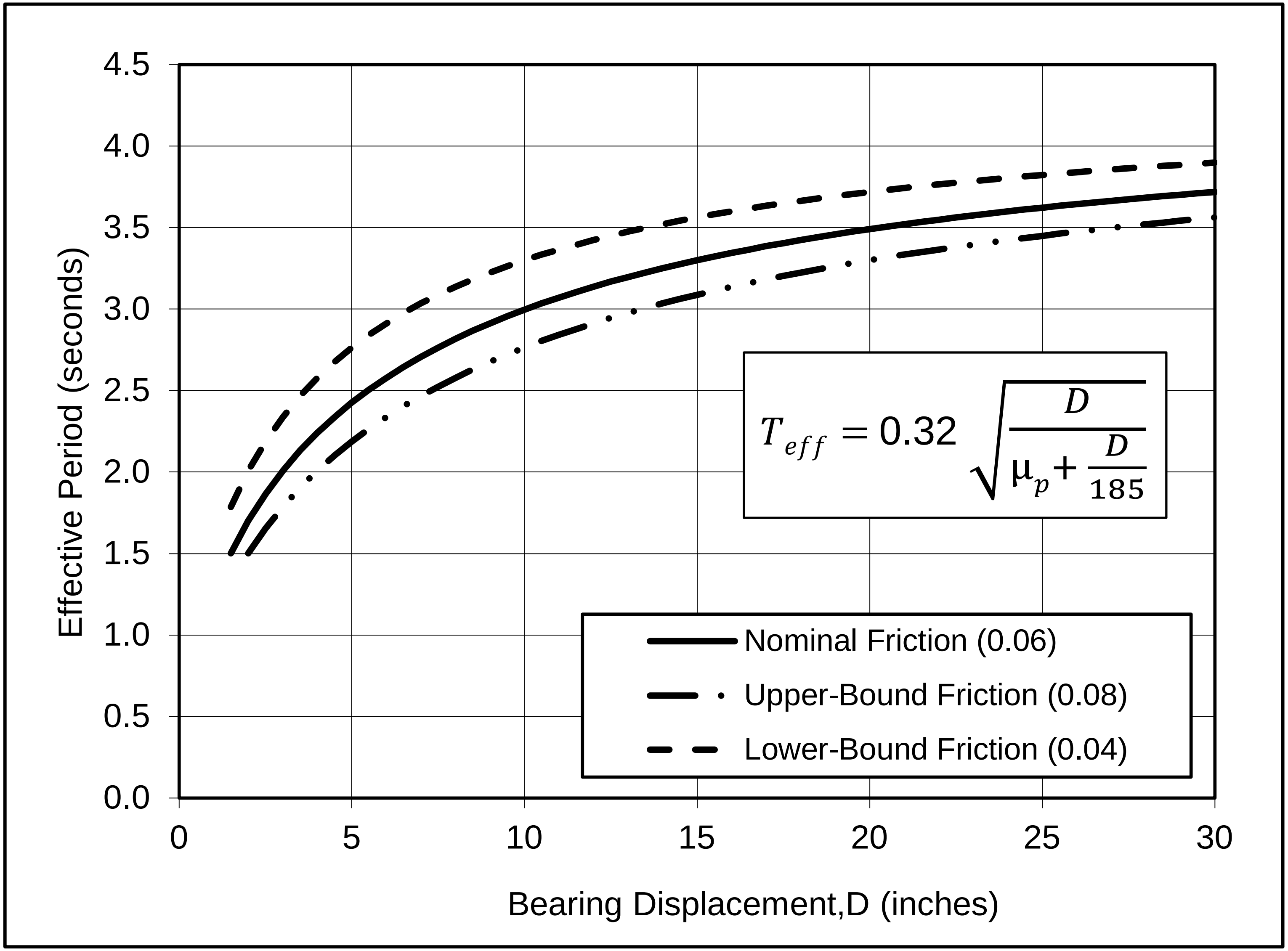
		Cycle	Keff (kip/in/kip.)	EDC (kip-in/kip.)	Friction	Damping
Avg. Vert. Load (kips)	383					
Max. Vert. Load (kips)	467	1 st.	0.00773	6.5466	0.063	19.9%
Min. Vert. Load (kips)	304	2nd	0.00767	6.1841	0.059	19.0%
Peak Velocity (in/sec)	4.8	3rd.	0.00766	6.1513	0.059	18.9%
		Avg.	0.00769	6.2940	0.061	19.3%

Modeling and Analysis
Force-Deflection Behavior of Double-Concave FPS Bearing

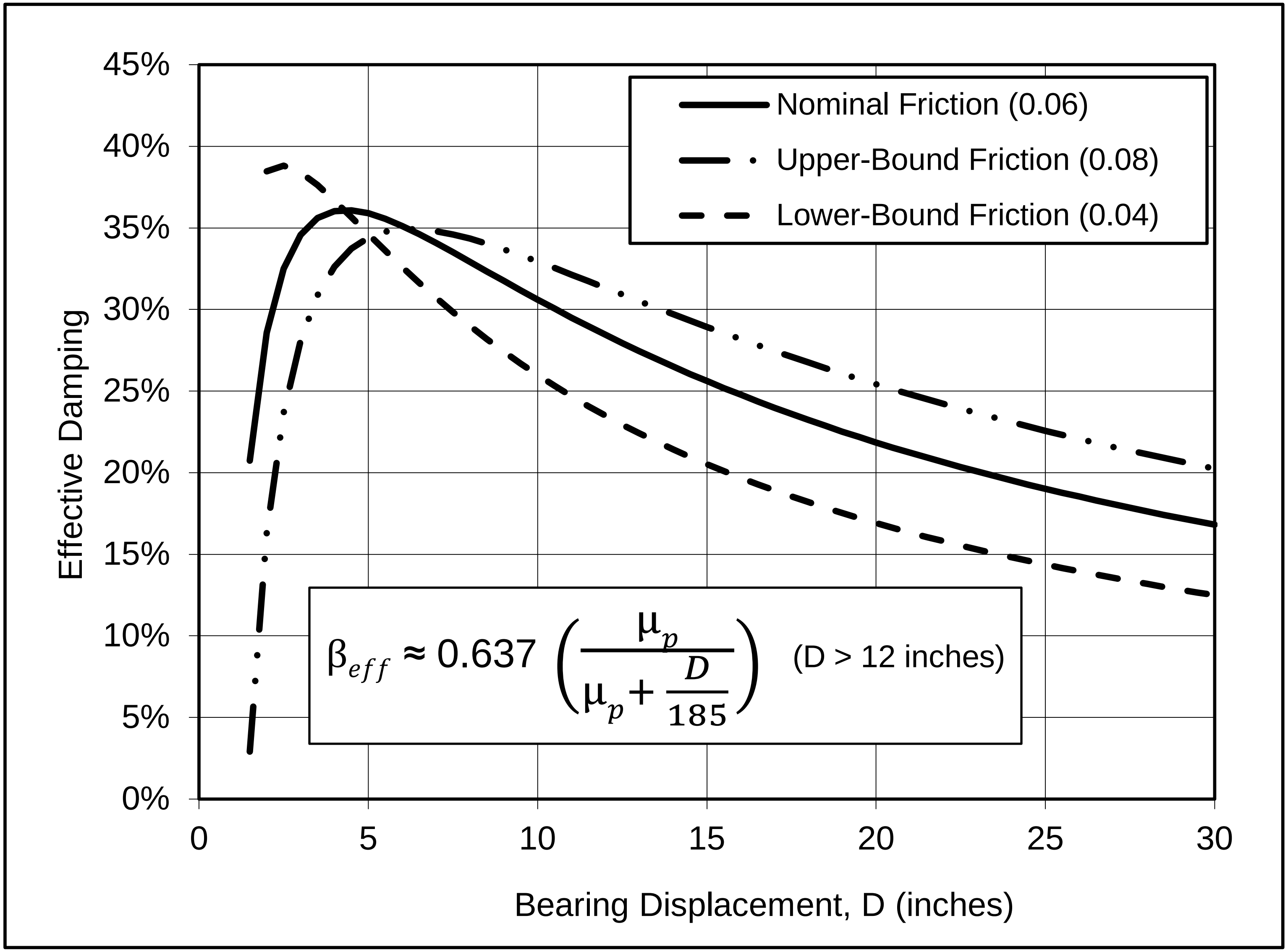


Modeling and Analysis

Effective Period of Double-Concave FPS Bearing



Modeling and Analysis
Effective Damping of Double-Concave FPS Bearing



Dynamic Lateral Response Procedures
RSA and RHA Procedures

- General – While the equivalent lateral force (ELF) procedure is useful for preliminary design, the *Standard* requires dynamic analysis for most isolated structures (and is commonly used for design even when not required)
- Response Spectrum Analysis (RSA) Procedure – RSA is useful for design of the superstructure which remains essentially elastic for design earthquake ground motions
- Response History Analysis (RHA) Procedure – RHA procedure is useful for verification of maximum isolation system displacement, etc., for MCE_R ground motions

Dynamic Lateral Response Procedures Minimum Design Criteria

- The *Standard* encourages the use of dynamic analysis but recognizes that along with the benefits of more complex model methods also comes an increased chance of error – to avoid possible under-design, the Standard establishes lower-bound limits of the results of RSA and RHA as a percentage of the ELF design parameter:

ELF Design Parameter		Percent of ELF	
Description	Symbol	RSA	RHA
Total Design Displacement	D_{TD}	90%	90%
Total Maximum Displacement	D_{TM}	80%	80%
Design Force – Isolation System (and below)	V_b	90%	90%
Design Force - Irregular Superstructure	V_s	100%	80%
Design Force – Regular Superstructure	V_s	80%	60%

Dynamic Lateral Response Procedures
Modeling Requirements

- Configuration - Dynamic analysis models should account for:
  - Spatial distribution of individual isolator units
  - Effects of actual (and accidental) mass eccentricity
  - Overturning forces and uplift of individual isolator units
  - Variability of isolation system properties (i.e., upper-bound and lower-bound values of stiffness and damping)
- Nonlinear Properties of the Isolators – Model should incorporate nonlinear properties of isolators determined from testing of prototype units (e.g., consistent with effective stiffness and effective damping properties of the ELF procedure)
- Nonlinear Properties of the Superstructure – Model should incorporate nonlinear properties of the superstructure, if RSA is used to justify loads less than those permitted for ELF (not typical)

Dynamic Lateral Response Procedures
Response Spectrum Analysis (RSA)

- Amplitude-dependent values of isolator properties:
  - Same effective stiffness and effective damping properties of isolators as those of the ELF procedure (including separate models/analyses of maximum and minimum values of effective stiffness)
- Modal Damping
  - Effective damping of isolated modes limited to 30 percent of critical
  - Higher modes typically assumed to have 2 to 5 percent damping
- 100%-30% Combination of Horizontal Earthquake Effects
  - Q_E = Max $(1.0Q_{EX} + 0.3Q_{EY}, 0.3Q_{EX} + 1.0Q_{EY})$
- Story Design Shear Force Limit
  - Design story shear forces are limited to those of the ELF distribution (over height) anchored to the RSA value of design base shear, V_s

Dynamic Lateral Response Procedures Response History Analysis (RSA)

- Explicit modeling of nonlinear properties:
  - Typical for modeling of Isolator units
  - Not typical for other elements of the structure
- At least 3 earthquake records:
  - Design based on the maximum response of the 3 records
  - Design based on the average response if 7, or more, records
- Earthquake record selection and scaling:
  - Records are selected with site properties (e.g., soil type), site-to-source distances, and source properties (i.e., fault type, magnitude, etc.) consistent with those that dominate seismic hazard at the site of interest
  - Selected records are scaled to match the “target” spectrum of either design earthquake or MCE_R ground motions over the period range of interest (e.g., $0.5T_M$ to $1.25T_M$).

Emergency Operations Center Design Example Overview

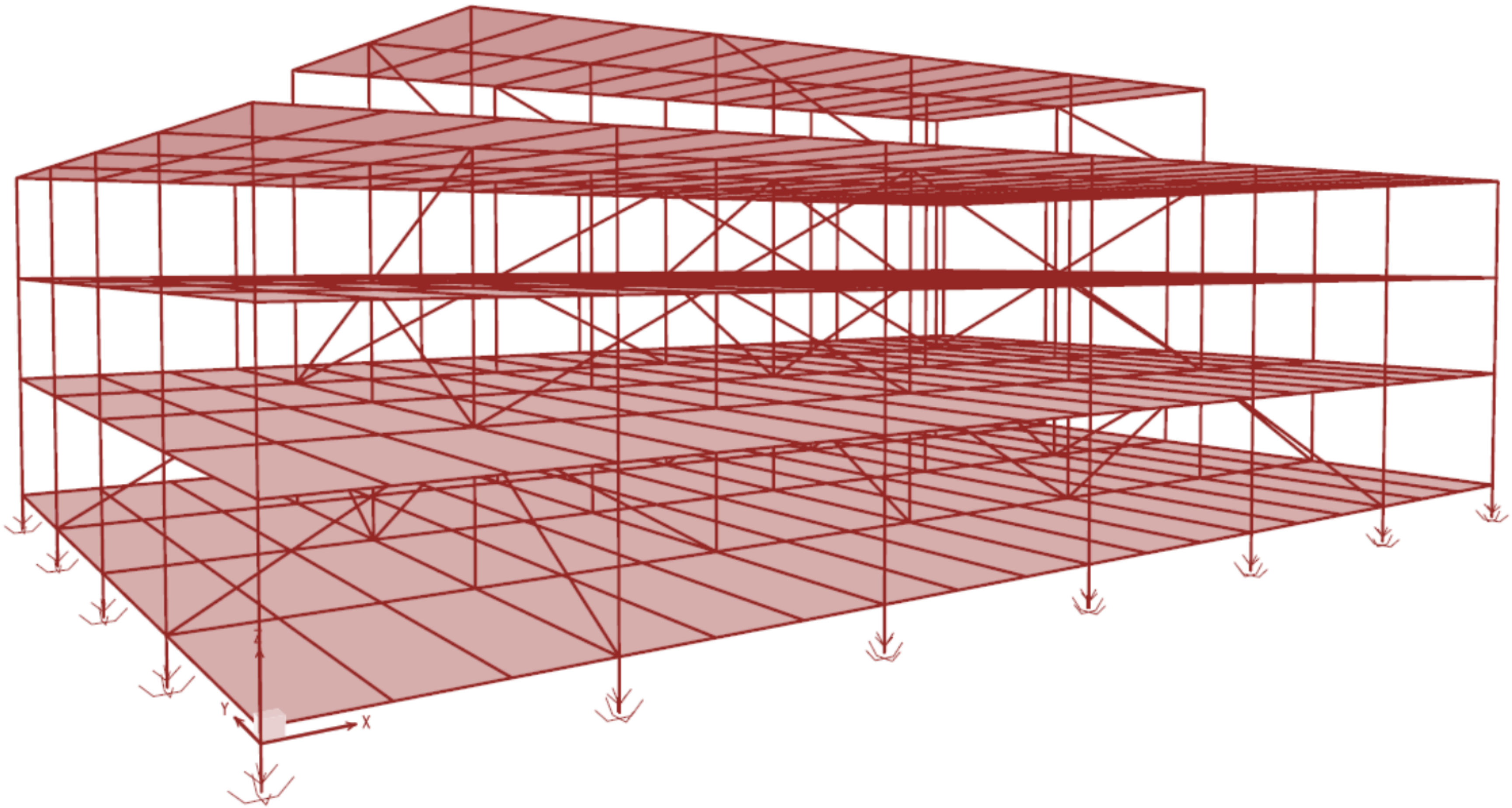
- Design example illustrates the following:
  - Determination of seismic design parameters
  - Preliminary design using ELF procedures
  - Final design (design verification using dynamic analysis)
  - Specification of isolation system testing criteria
- Hypothetical emergency operations center (EOC)
  - Essential Facility - Risk Category IV
  - High Seismic Site – 6 km from an active fault (SDC F)
  - Configuration – approx. 50,000 sf, 3-stories plus mechanical penthouse with helipad
  - Structure - Steel special concentric braced frames
  - Isolators – Double-concave FPS sliding bearings (35 isolators)

Emergency Operations Center Design Example
Structural Design Criteria – Special SCBF

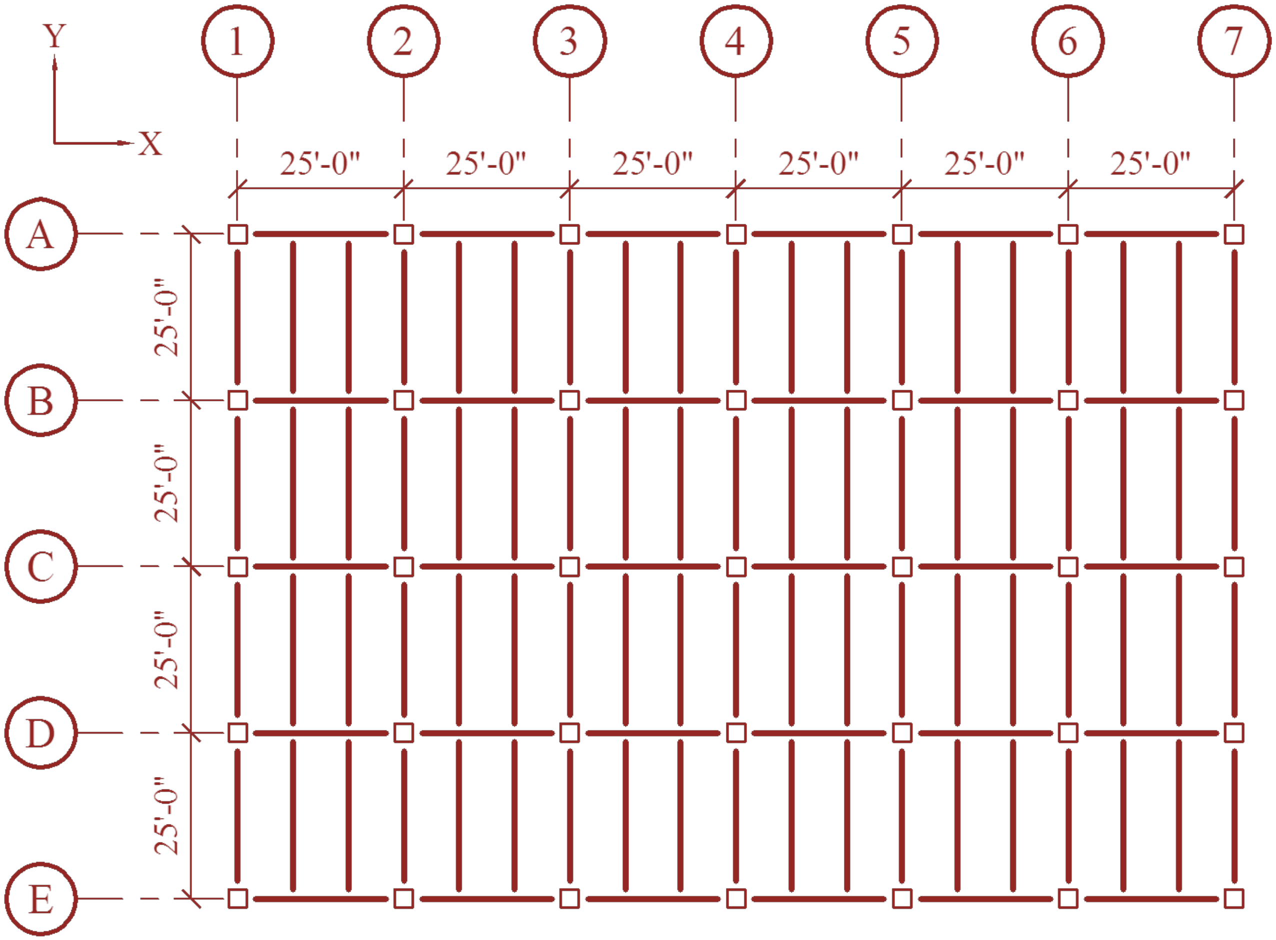
- Height limit (Table 12.2-1, SDC F) $h < 100$ ft
- Response modification factor (R and R_I):
  - Fixed-base (Table 12.2-1): $R = 6$
  - Isolated (Sec. 17.5.4.2): $R_I = 2$ ($C_d = 2$)
- Importance factor, I_e (Risk Category IV):
  - Fixed-base (Sec. 11.5.1/Table 1.5-2): $I_e = 1.5$
  - Isolated (Sec. 17.2.1): $I_e = 1.0$
- Plan irregularity of superstructure (Table 12.3-1): None
- Vertical irregularity of superstructure (Table 12.3-2): None
- Lateral response procedure (Sec. 17.4.1, $S_1 > 0.6$g): Dynamic Analysis
- Redundancy factor, ρ:
  - Fixed-base (Table 12.3.4): $\rho > 1.0$
  - Isolated (inferred): $\rho = 1.0$

Emergency Operations Center Design Example

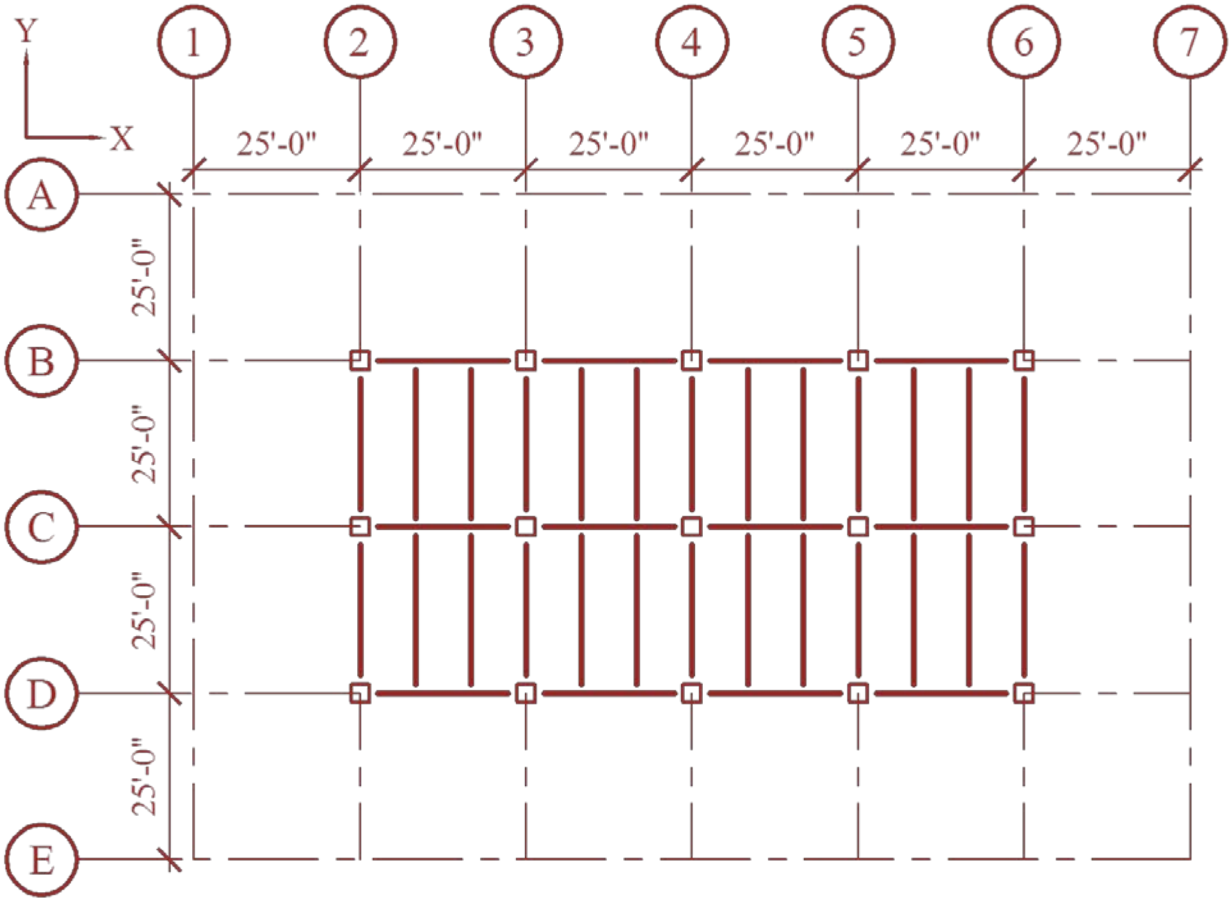
3-D ETABS Model of the Structure



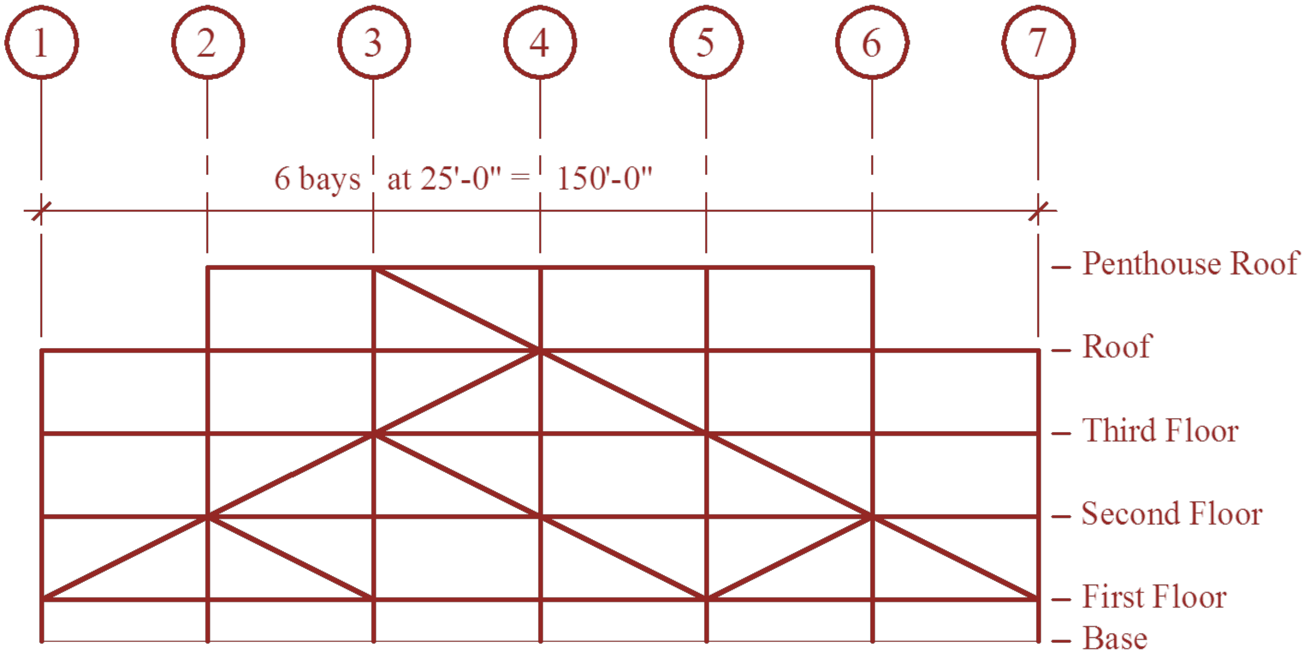
Emergency Operations Center Design Example
Typical Floor Framing Plan



Emergency Operations Center Design Example
Penthouse Roof Framing Plan

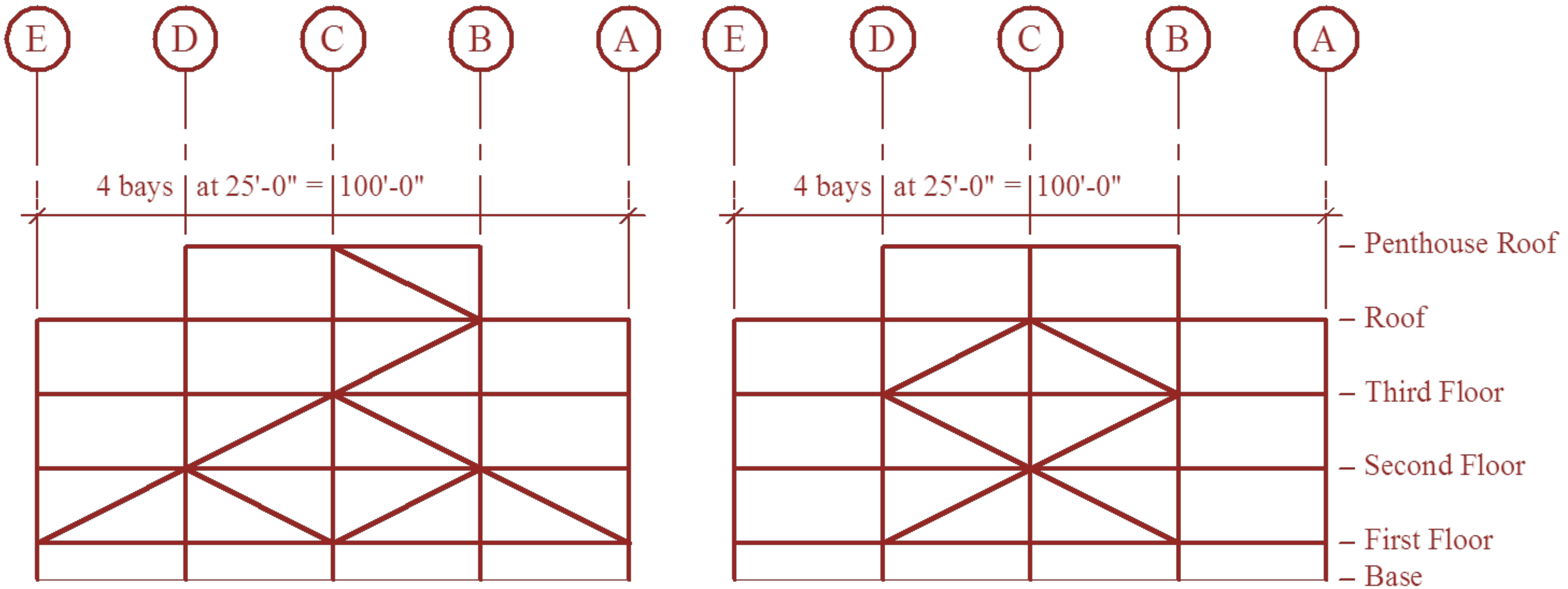


Emergency Operations Center Design Example
Longitudinal Bracing Elevation



Lines B and D

Emergency Operations Center Design Example
Transverse Bracing Elevations



(a) Lines 2 and 6

(b) Line 4

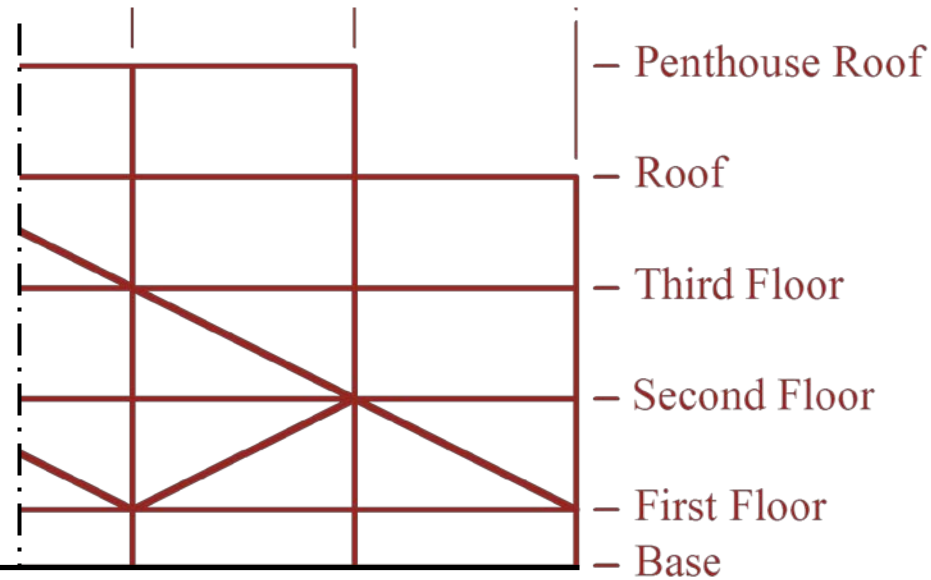
Emergency Operations Center Design Example
Basic Design Requirements

- Seismic Codes and Standards
  - General: ASCE 7-05 (*Standard*)
  - Seismic: 2009 NEHRP Recommended Provisions
  - Other Loads (load combinations): 2006 IBC
- Materials

• Concrete:	floor slabs	f_c' = 3 ksi
	foundations	f_c' = 5 ksi
	normal weight	150 psf
• Steel:	columns	F_y = 50 ksi
	primary girders (1^{st}-floor)	F_y = 50 ksi
	other girders and beams	F_y = 36 ksi
	braces	F_y = 46 ksi
• Steel Deck	3-inch deep, 20-gauge deck	

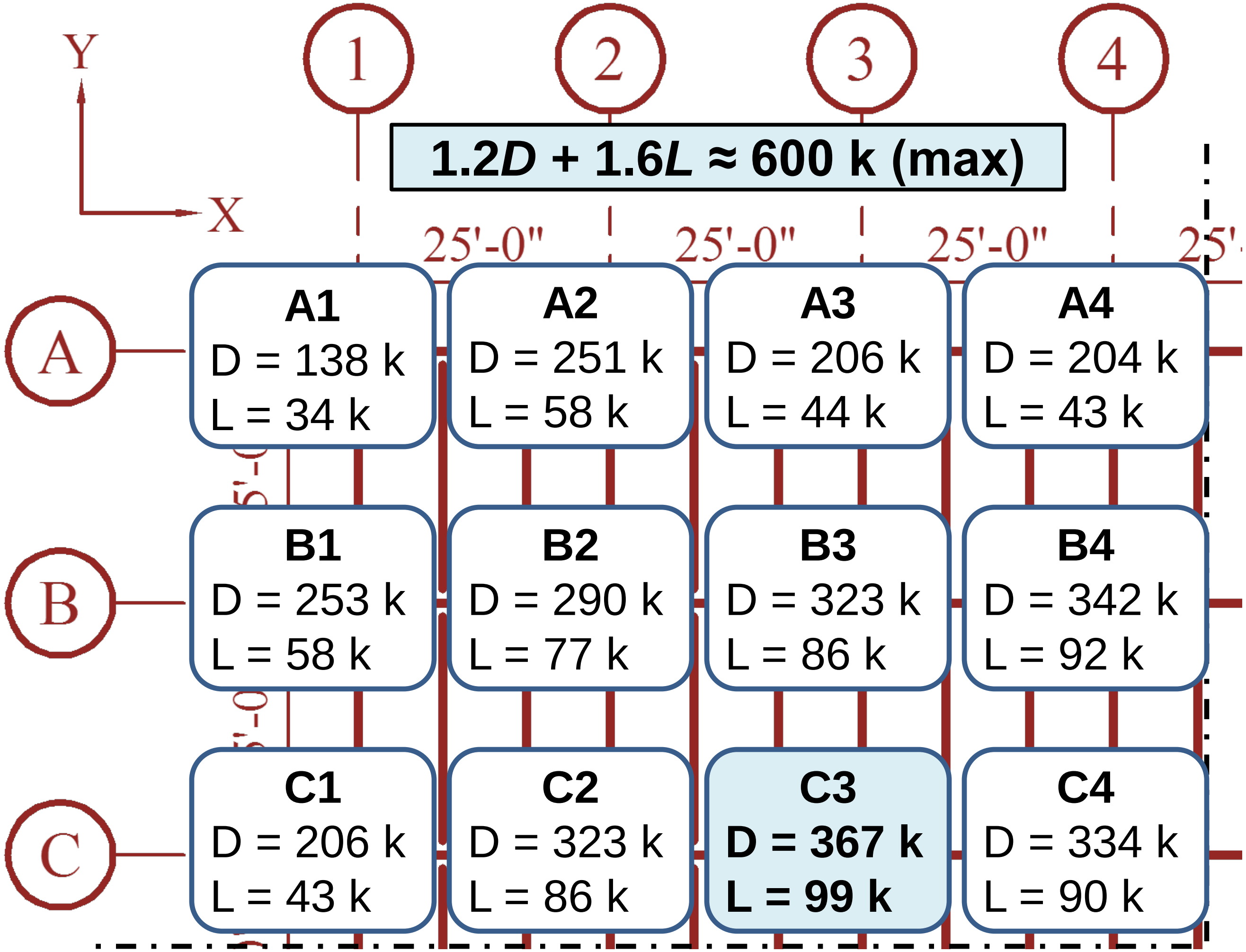
Emergency Operations Center Design Example
Gravity Loads (by elevation)

Elevation	Load	Kips	
Penthouse Roof	W_{PR}	794	
Roof	W_R	2,251	
3^{rd} Floor	W_3	1,947	
2^{nd} Floor	W_2	1,922	
1^{st} Floor	W_1	2,186	
Total Weight	W	9,100	Total dead load (D) weight on isolators
Total Live	L	5,476	Total unreduced live load
Reduced Live	L	2,241	Total reduced live load (L) weight on isolators



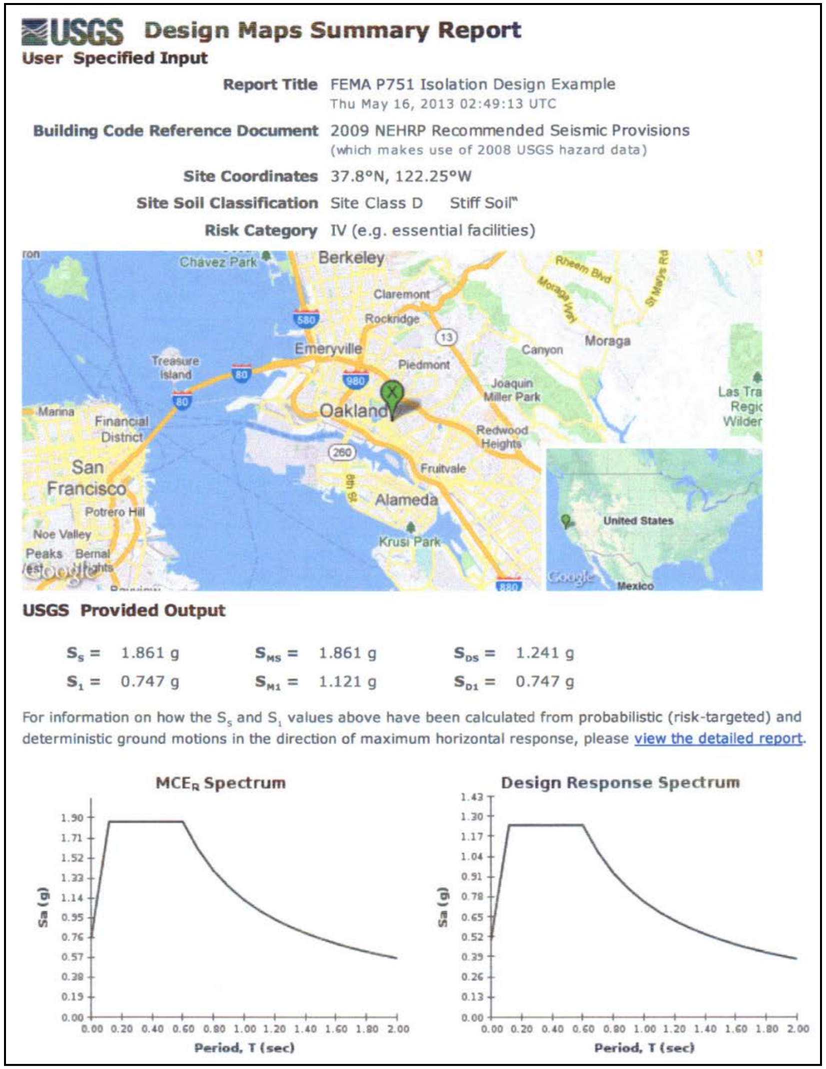
Emergency Operations Center Design Example

Maximum Gravity (Dead/Live Load) Forces on Isolators

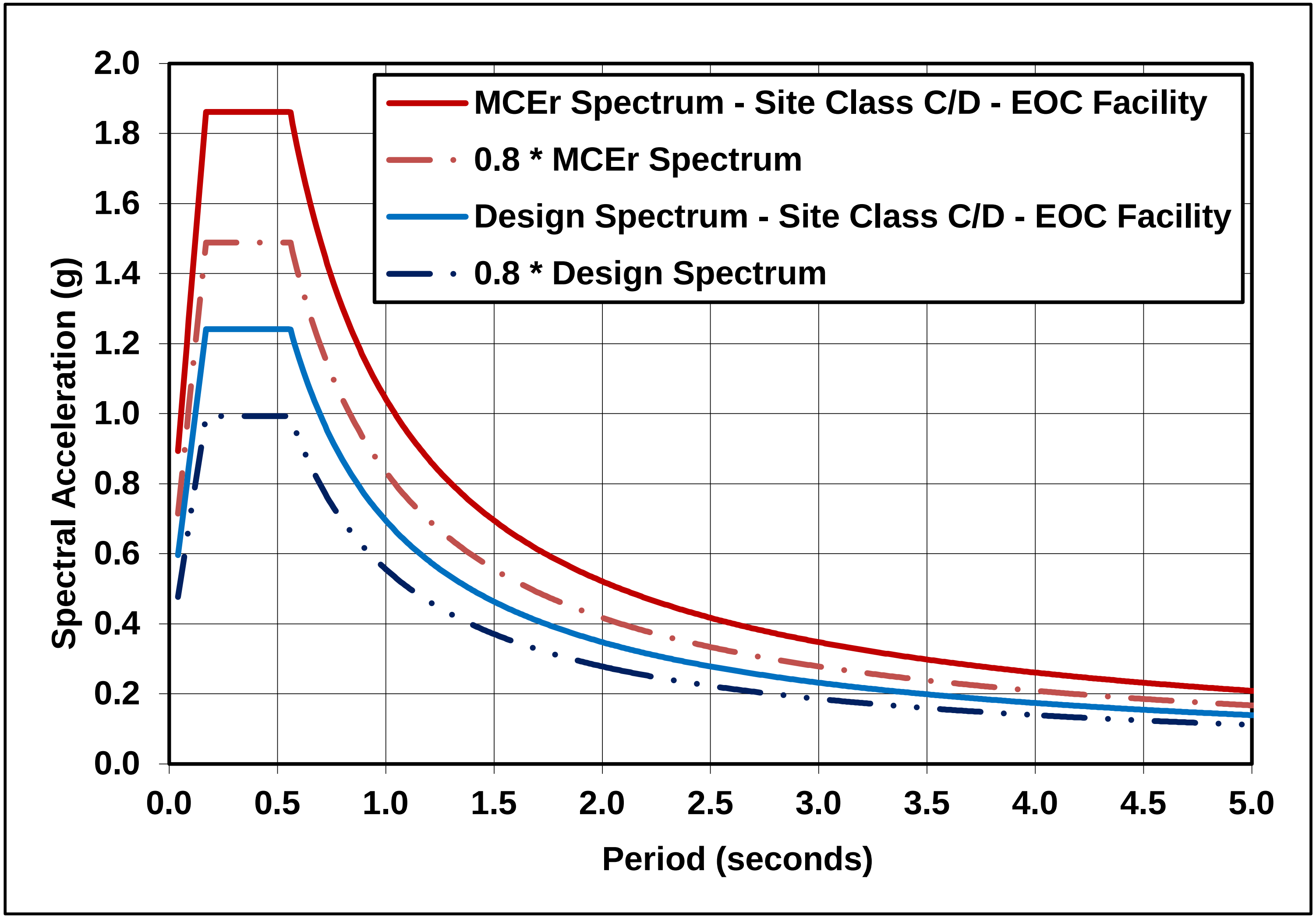


Emergency Operations Center Design Example
Seismic Design Parameters (USGS)

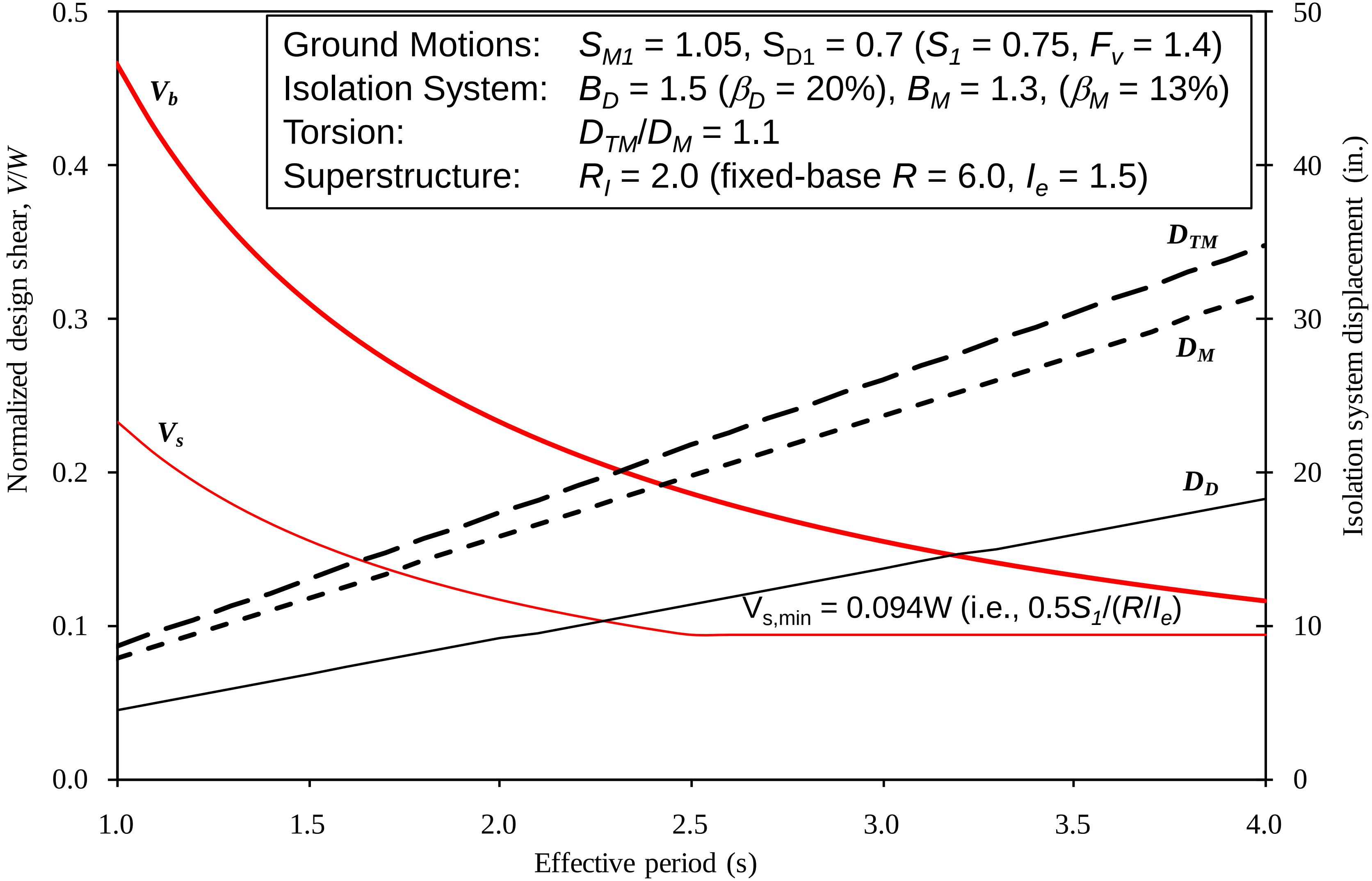
- Design Parameters at USGS website: http://geohazards.usgs.gov/designmaps/
- User enters design data:
  - Code: 2009 NEHRP Provisions
  - Site Classification: Site Class C or D
  - Risk Category: Risk Category IV
  - Site Lat. 37.80^0 Site Long. - 122.25^0
- Summary report provides:
  - Echo print of design data
  - Map showing site location
  - MCE_R and design ground motions:
    - S_{MS} = 1.861 g; S_{DS} = 1.241 g
    - S_{M1} (D) = 1.121 g; S_{D1} = 0.747 g
    - S_{M1} (C) = 0.972 g; S_{D1} = 0.648 g
  - Plots of MCE_R and Design Spectra
  - Supporting Data (long report)



Emergency Operations Center Design Example
Design and MCE_R Response Spectra



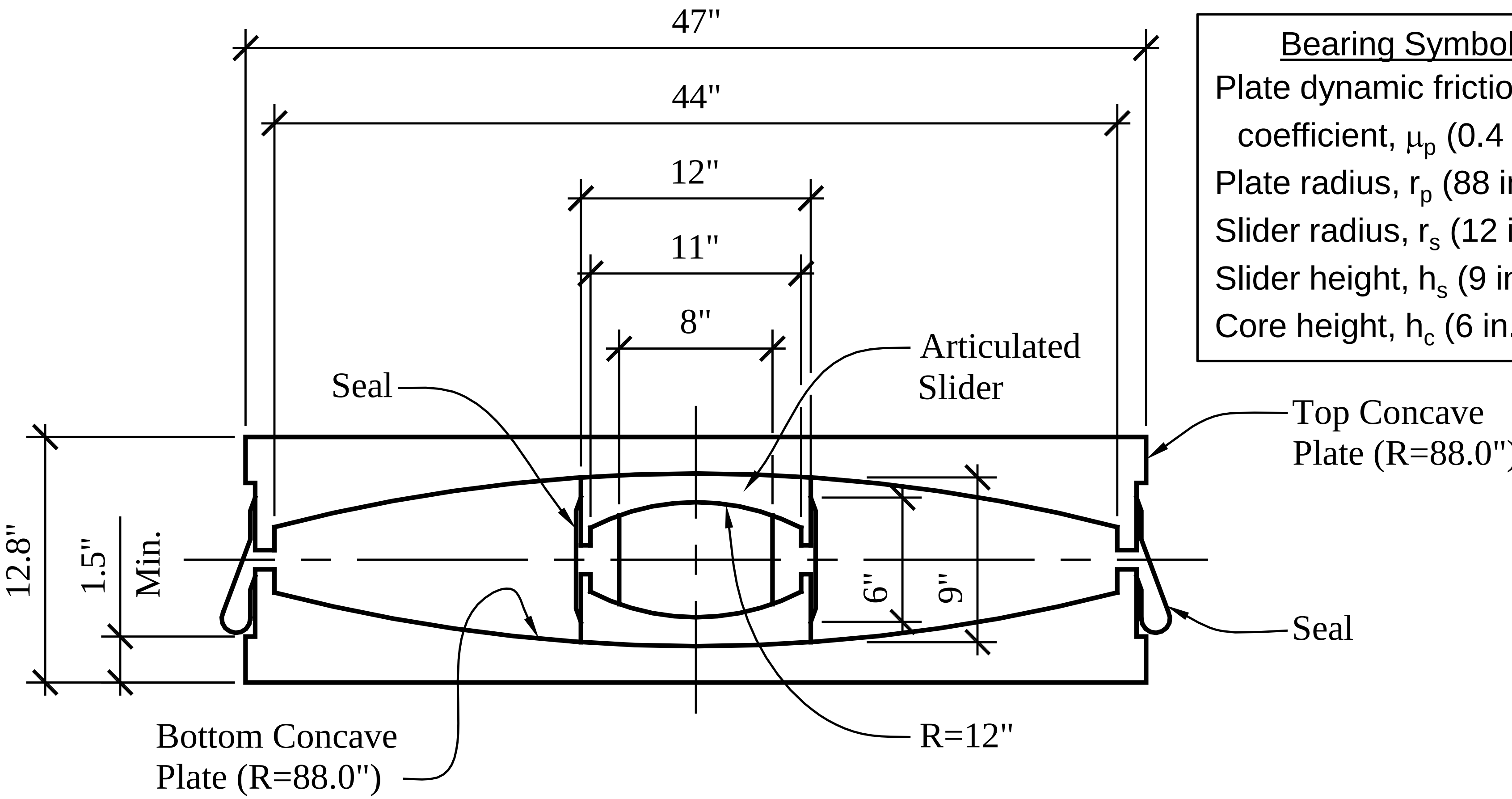
Equivalent Lateral Force Procedure
Example Values of Design Parameters (Steel SCBF)



Emergency Operations Center Design Example
Preliminary Design – Isolation System

- Isolation system (isolator bearing) selection criteria:
  - Large maximum displacement capacity, $D_{TM} \geq 30$ inches to accommodate very high seismic demands
  - Effective period (design level), $T_D \geq 2.5$ sec., to reduce forces on superstructure and overturning loads on bearings
  - Effective damping (MCE_R level), $\beta_M \geq 10\%$, to limit MCE_R displacement
  - High-damping rubber (HDR) bearings, lead-rubber (LR) bearings and sliding (FPS) bearings are all possible choices
- Double-concave FPS bearing (FPT8844/12-12/8-6) selected:
  - Maximum displacement capacity of about 33 inches
  - Effective period, $T_D \geq 3.5$ sec. at displacement, D > 16 inches
  - Effective damping, $\beta_M \geq 12.5\%$ at displacement, D = 30 inches
  - Load capacity: > 500 kips (long term), > 1,000 kips (short term)

Modeling and Analysis
Double-Concave FPS Bearing



Bearing Symbols

Plate dynamic friction coefficient, μ_p (0.4 - 0.8)

Plate radius, r_p (88 in.)

Slider radius, r_s (12 in.)

Slider height, h_s (9 in.)

Core height, h_c (6 in.)

Section view of the double-concave friction pendulum bearing FPT8844/12-12/8-6)

Emergency Operations Center Design Example
Seismic Force Analysis – ETABS Model

- A linear, 3-D (ETABS) model of the EOC structure was used to expedite calculation of the following loads and load combinations:
  - Gravity loads, including maximum long-term loads on isolators:
    - 1.2D + 1.6L
  - Superstructure design forces for combined gravity and reduced design earthquake load effects ignoring potential uplift of isolators (pushover using ELF lateral forces):
    - $1.2D + 0.5L + E = (1.2 + 0.2S_{DS})D + 0.5L + Q_{DE/2}$
    - $0.9D – E = (0.9 – 0.2S_{DS})D - Q_{DE/2}$
  - Isolation system and foundation design forces for combined gravity and unreduced design earthquake loads and permitting local uplift of individual isolator units (pushover using ELF lateral forces):
    - $1.2D + 0.5L + E = (1.2 + 0.2S_{DS})D + 0.5L + Q_{DE}$
    - $0.9D – E = (0.9 – 0.2S_{DS})D - Q_{DE}$

Emergency Operations Center Design Example
Seismic Force Analysis – ETABS Model

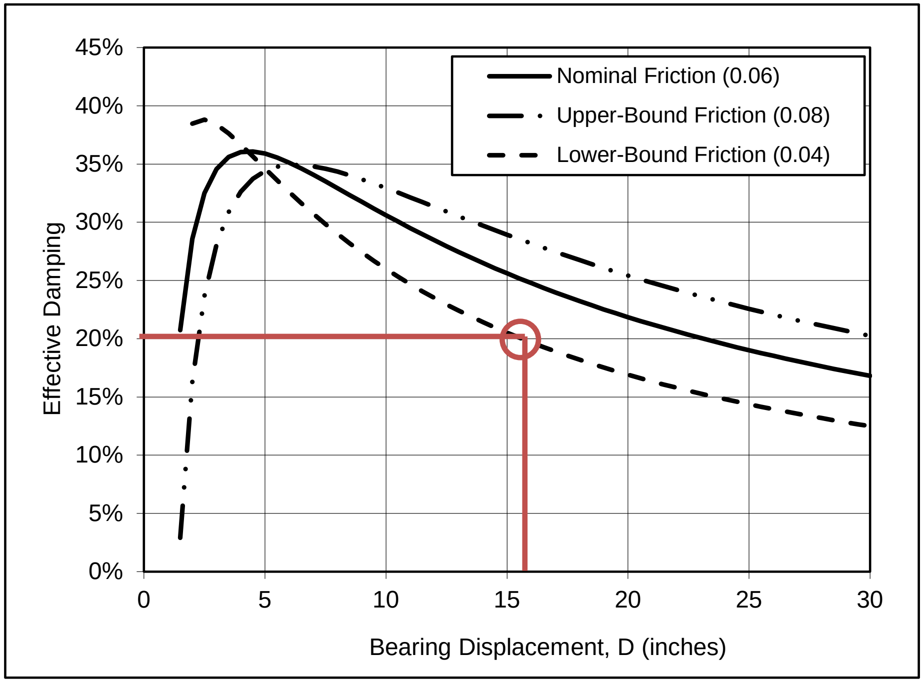
- A linear, 3-D (ETABS) model of the EOC structure was used to expedite calculation of the following loads and load combinations:
  - Maximum short-term (downward) and minimum short-term (downward) forces on individual isolators for combined gravity and unreduced design earthquake loads (pushover using ELF lateral forces and permitting local uplift of individual isolators)
    - $1.2D + 1.0L + E = (1.2 + 0.2S_{MS})D + 1.0L + Q_{DE}$
    - $0.9D – E = (0.9 – 0.2S_{MS})D - Q_{DE}$
  - Maximum short-term (downward) and minimum short-term (maximum uplift displacement) forces on individual isolators for combined gravity and unreduced MCE_R loads (pushover using ELF lateral forces and permitting local uplift of individual isolators)
    - $1.2D + 1.0L + E = (1.2 + 0.2S_{MS})D + 1.0L + Q_{MCE}$
    - $0.9D – E = (0.9 – 0.2S_{MS})D - Q_{MCE}$

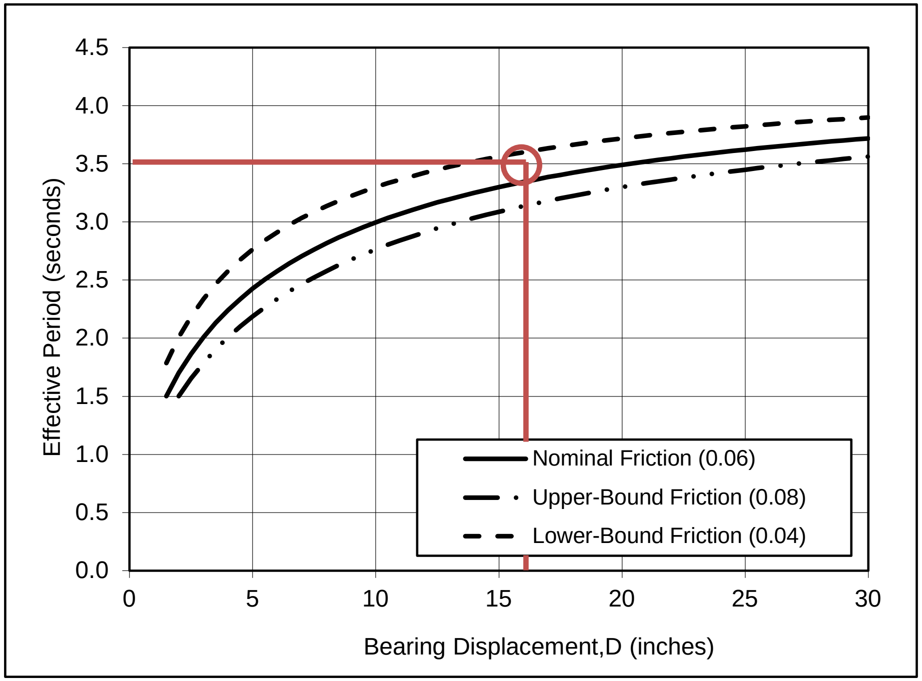
Emergency Operations Center Design Example
Preliminary Design – ELF Displacement

- Design Displacement, D_D:

$$D_D = \left(\frac{g}{4\pi^2}\right)\frac{S_{D1}T_D}{B_D} = (9.8)\frac{0.7(3.5)}{1.5} = 16.0 \text{ in.}$$

B_D, B_M	β_D, β_M
1.2	10%
1.35	15%
1.5	20%



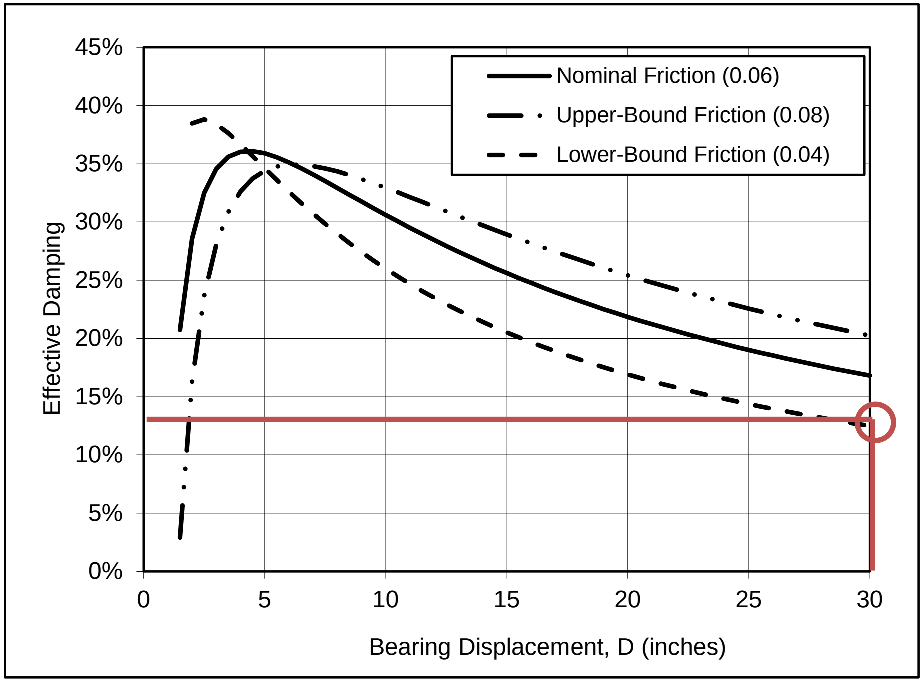


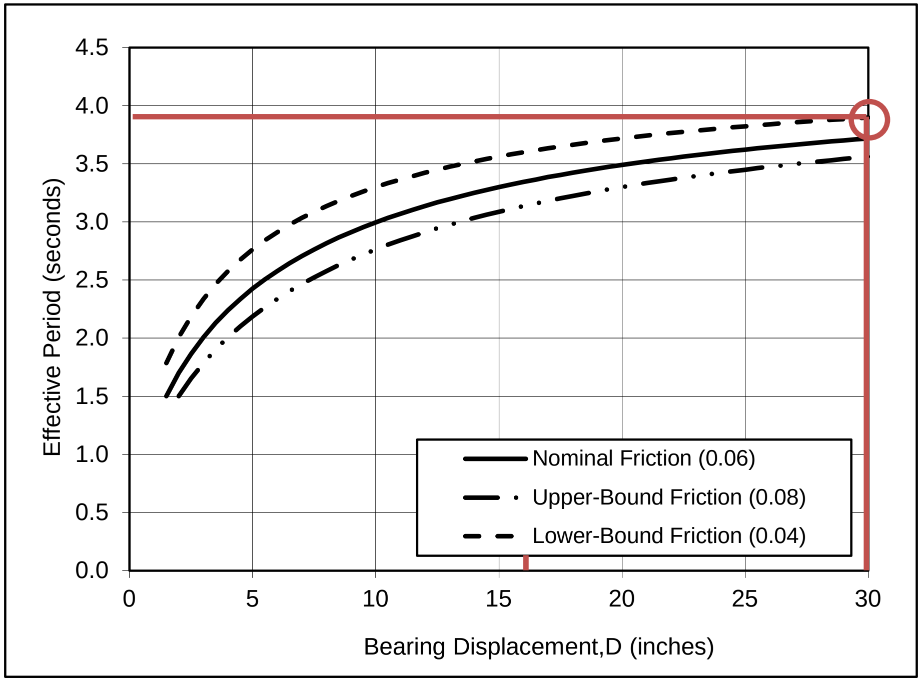
Emergency Operations Center Design Example
Preliminary Design – ELF Displacement

- Maximum Displacement, D_M:

$$D_M = \left(\frac{g}{4\pi^2}\right)\frac{S_{M1}T_M}{B_M} = (9.8)\frac{1.05(3.9)}{1.3} = 30.9 \text{ in.}$$

B_D, B_M	β_D, β_M
1.2	10%
1.35	15%
1.5	20%





Emergency Operations Center Design Example
Preliminary Design – ELF Displacement

- Total Design and Maximum Displacements, D_{TD} and $D_{TM,}$ (e = 0.05d):

$$D_{TD} = DD\left[1 + y\frac{12e}{b^2+d^2}\right] = 16\left[1 + 90\left(\frac{12(0.05)150}{100^2+150^2}\right)\right] = 16\ (1.25)$$

$$D_{TM} = DM\left[1 + y\frac{12e}{b^2+d^2}\right] = 30.9\left[1 + 90\left(\frac{12(0.05)150}{100^2+150^2}\right)\right] = 30.9\ (1.25)$$

- FPS bearings mitigate the effects of mass eccentricity, but additional displacement due to actual plus accidental torsion cannot be taken as less than 1.1 times translation-only displacement which corresponds to e = 0.02d for the geometry of the EOC building:

$$D_{TD} = DD\left[1 + y\frac{12e}{b^2+d^2}\right] = 16\left[1 + 90\left(\frac{12(0.02)150}{100^2+150^2}\right)\right] \geq 16\ (1.1) = 17.6\ in.$$

$$D_{TM} = DM\left[1 + y\frac{12e}{b^2+d^2}\right] = 30.9\left[1 + 90\left(\frac{12(0.02)150}{100^2+150^2}\right)\right] \geq 30.9\ (1.1) = 34\ in.$$

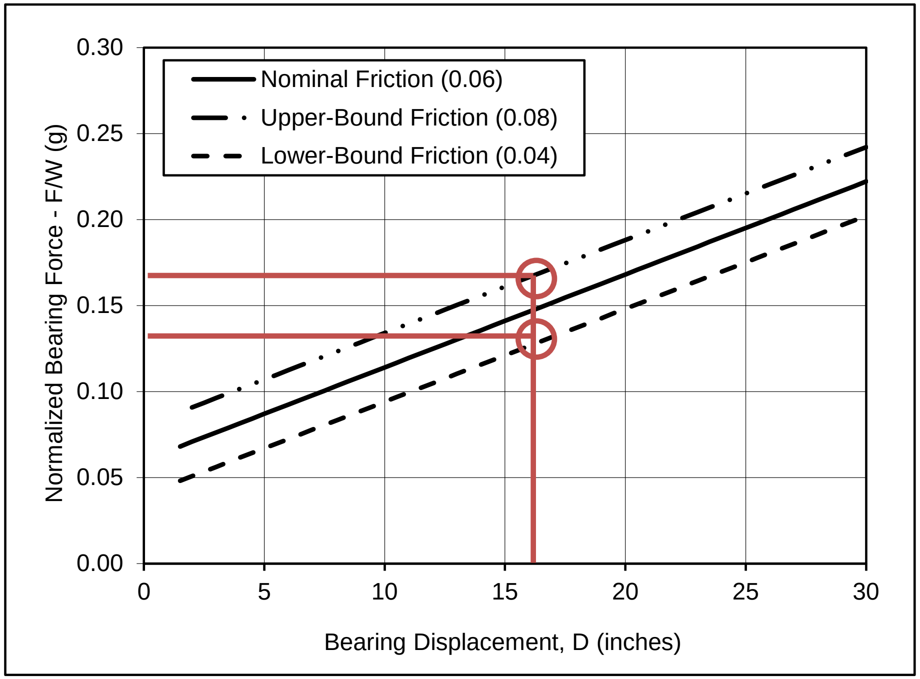
Emergency Operations Center Design Example
Preliminary Design – ELF Effective Stiffness

- Minimum and Maximum Effective Design Stiffness:

$$k_{D\min} = \left(\frac{4\pi^2}{g}\right)\frac{W}{T_D^2} = \left(\frac{1}{9.8}\right)\frac{9,100}{3.5^2} = 75.8 \text{ kips/in.}$$

Maximum effective stiffness is estimated to be about 1.2 times minimum effective displacement at the maximum displacement, D_D = 16 inches

$$k_{D\max} = 1.2(75.8) = 91.0 \text{ kips / in.}$$



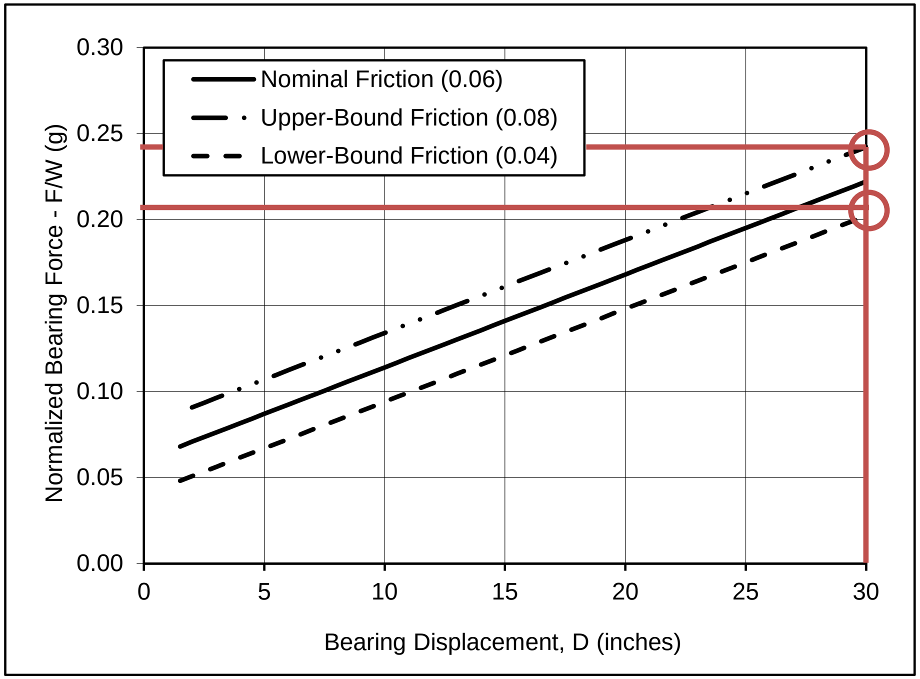
Emergency Operations Center Design Example
Preliminary Design – ELF Effective Stiffness

- Minimum and Maximum Effective $\underline{MCE_R}$ Stiffness:

$$k_{M\,min} = \left(\frac{4\pi^2}{g}\right)\frac{W}{T_D^2} = \left(\frac{1}{9.8}\right)\frac{9{,}100}{3.9^2} = 61.1 \text{ kips/in.}$$

Maximum effective stiffness is estimated to be about 1.15 times minimum effective displacement at the maximum displacement, D_M = 30.9 inches

$$k_{M\,max} = 1.15(61.1) = 70.3 \text{ kips / in.}$$



Emergency Operations Center Design Example

Preliminary Design – ELF Lateral Design Force

- Design of the Isolation System, foundation and structure below:

$$V_b = k_{Dmax} D_D = 91.0(16.0) = 1{,}456 \text{ kips} \qquad 0.16W$$

- Stability check of Isolation System for MCE_R response:

$$V_{MCE} = k_{Mmax} D_M = 70.3(30.9) = 2{,}172 \text{ kips} \qquad 0.24W$$

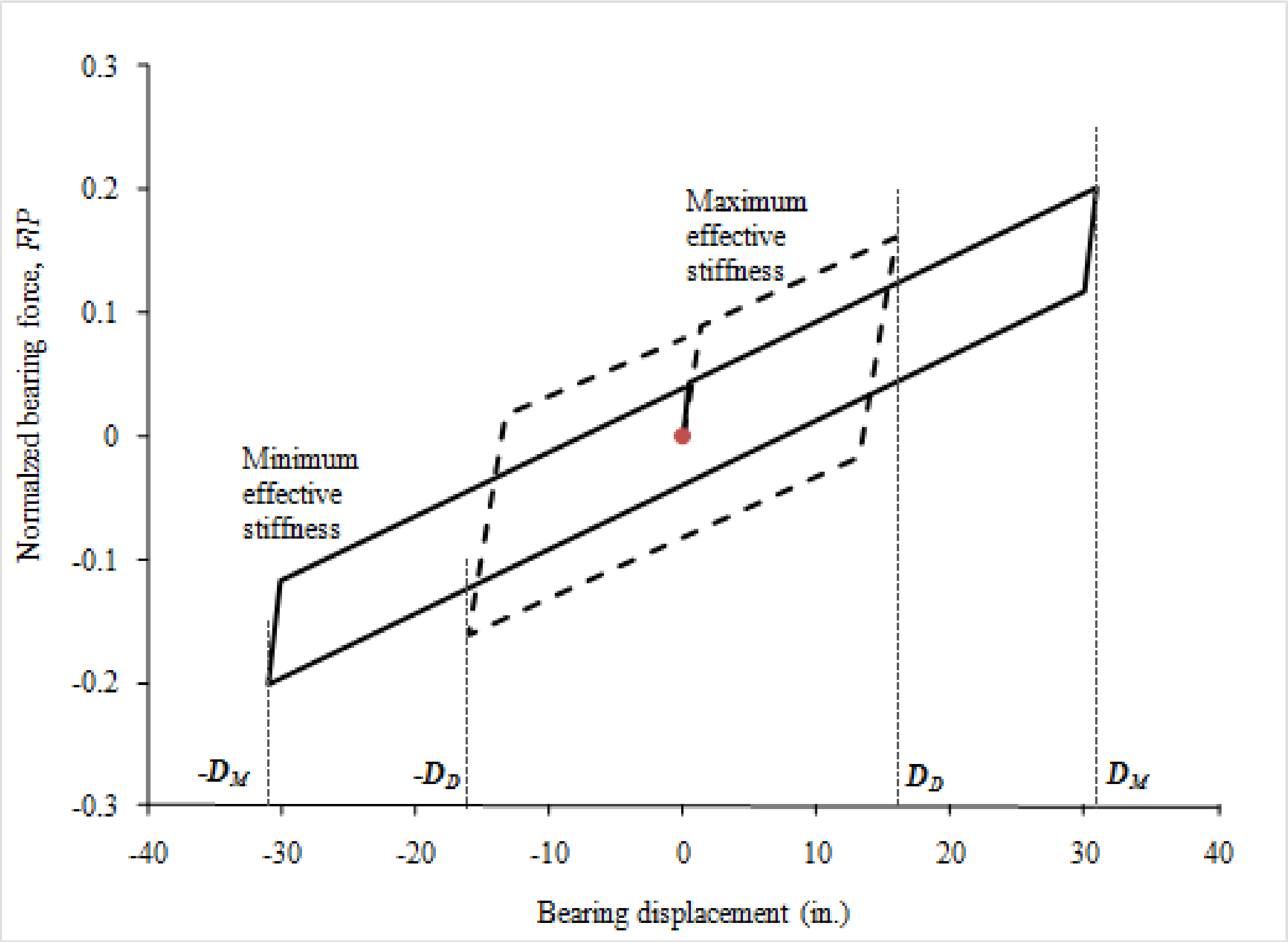
- Design of the structure above the Isolation System:

$$V_s = \frac{k_{D\max} D_D}{R_I} = \frac{91.0(16.0)}{2.0} = \sout{728 \text{ kips}} \qquad \sout{0.08W}$$

$$V_s = 0.5S_1/(R/I_e) = 0.5(0.75)/(6/1.5) = \sout{853 \text{ kips}} \qquad \sout{0.094W}$$

$$V_s = 1.5\mu_{P,\max} W = 1.5(0.08)9{,}100 = 1{,}092 \text{ kips} \qquad 0.12W$$

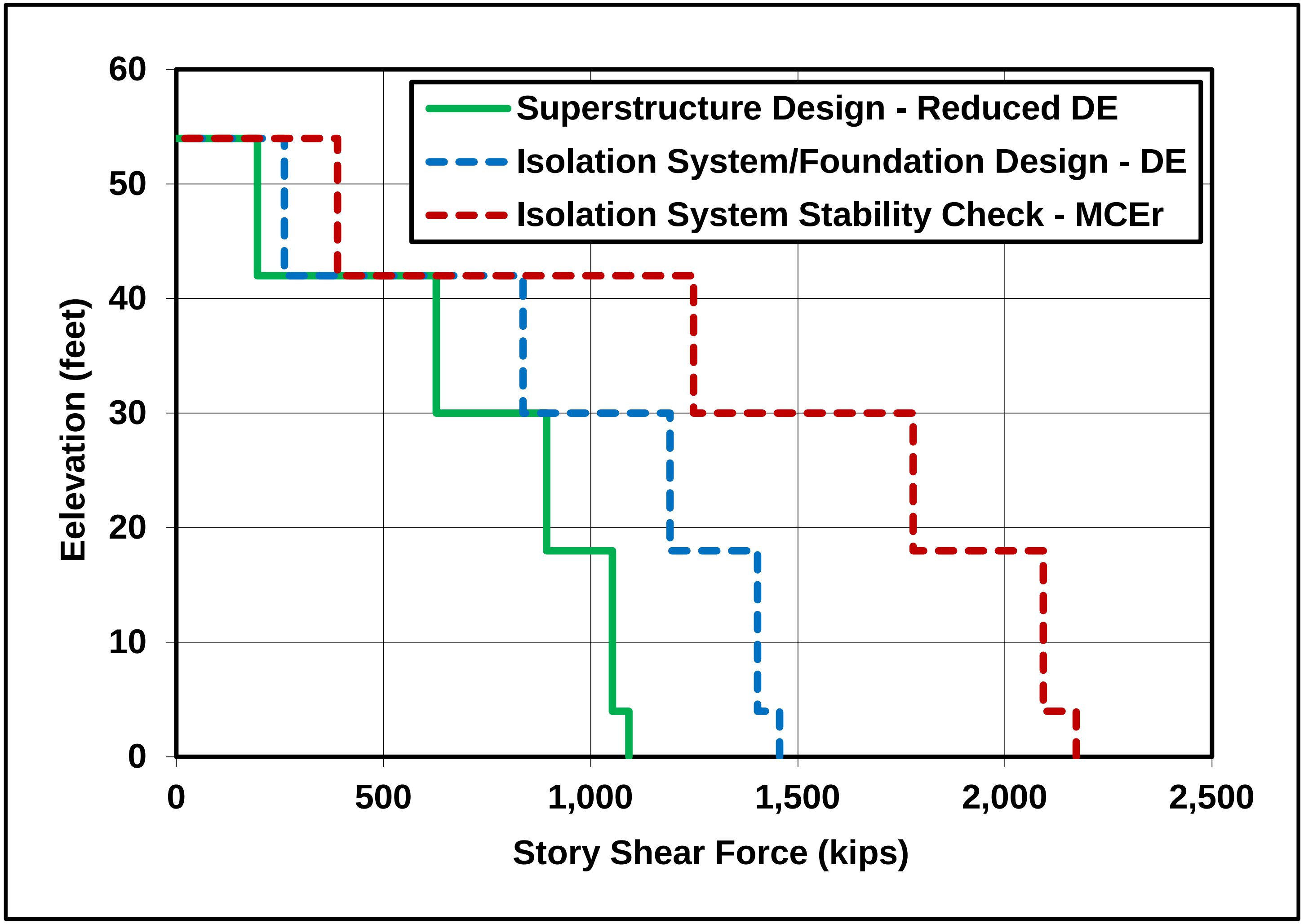
Emergency Operations Center Design Example
Preliminary Design - Hysteresis Loops Used for ELF Design



Emergency Operations Center Design Example
Preliminary Design – ELF Distribution of Lateral Design Force

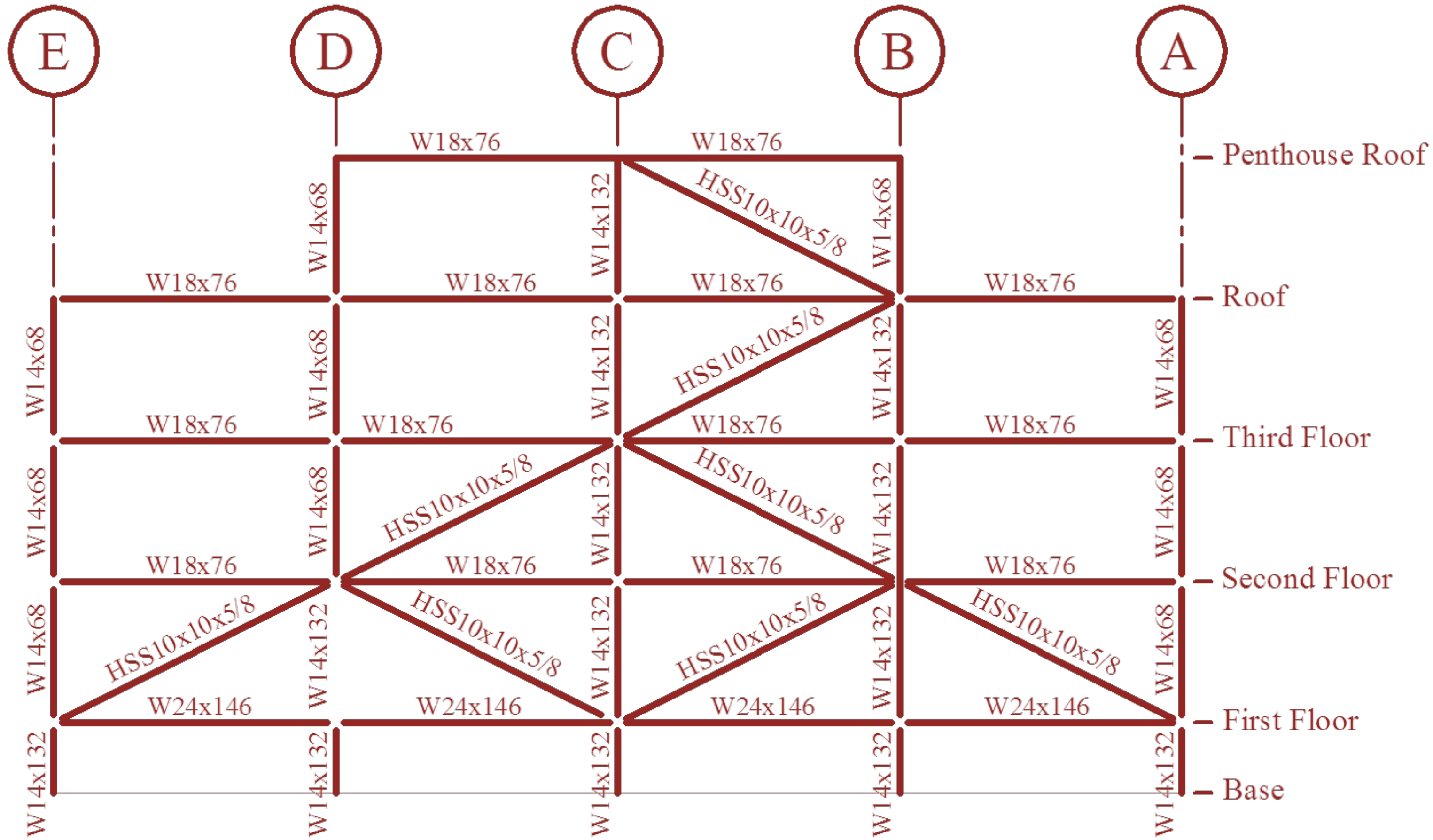
Floor level, x (Story)	Floor weight, w_x (kips)	Cumulative weight (kips)	Height above isolation system, h_x (ft)	Story force, F_x, (kips) (Standard Eq. 17.5-9)	Cumulative story force (kips)	Cum. force divided by cumulative weight
PH Roof	794		54			
(Penthouse)		794		196	196	25%
Roof	2,251		42			
(Third)		3,045		432	628	21%
Third Floor	1,947		30			
(Second)		4,992		267	895	18%
Second Flr.	1,922		18			
(First)		6,914		158	1,053	15%
First Floor	2,186		4			
(Isolation)		9,100		40	1,092	12%

Emergency Operations Center Design Example
Preliminary Design – ELF Distribution of Lateral Design Force



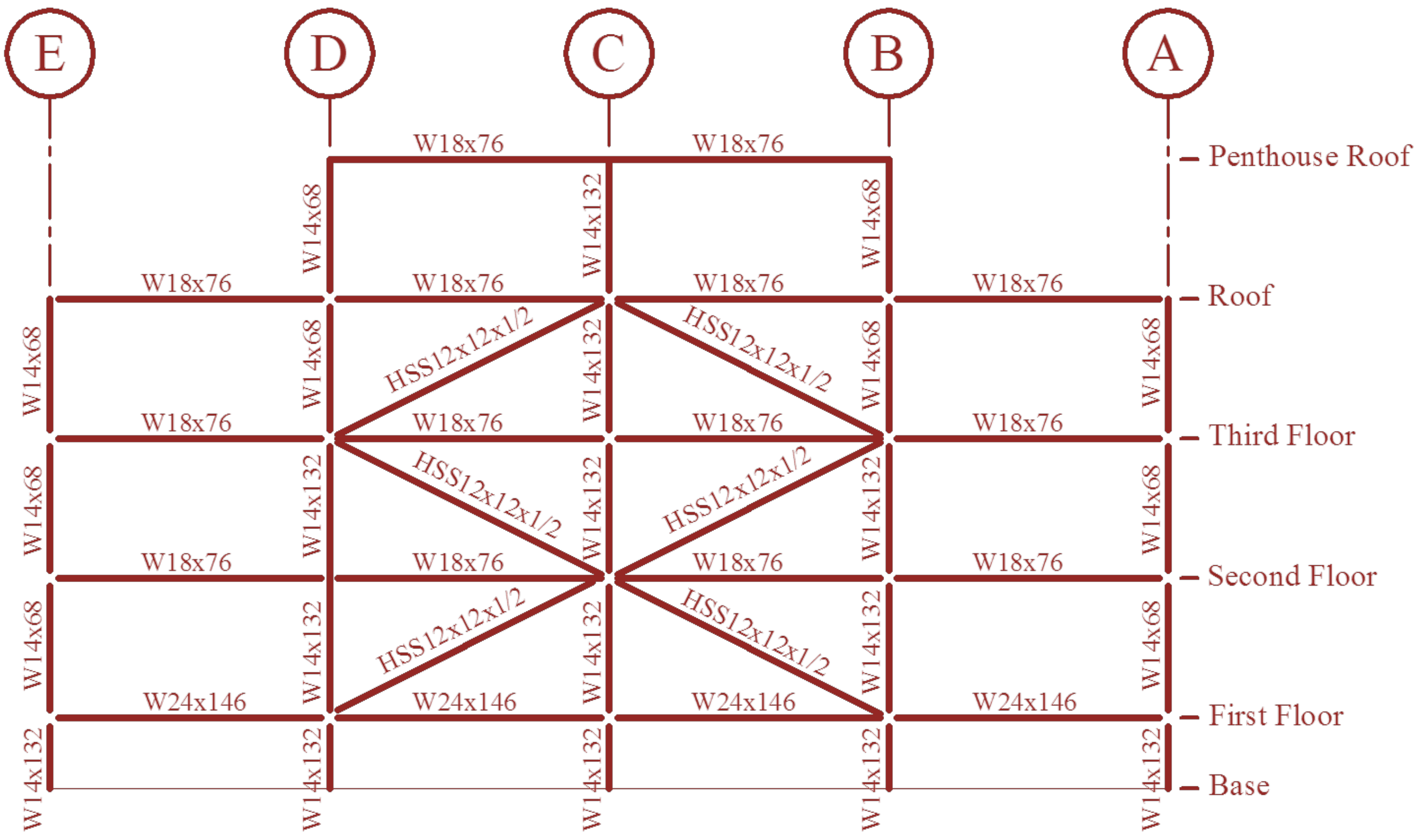
Emergency Operations Center Design Example

Framing on Lines 2 and 6 – Preliminary Design



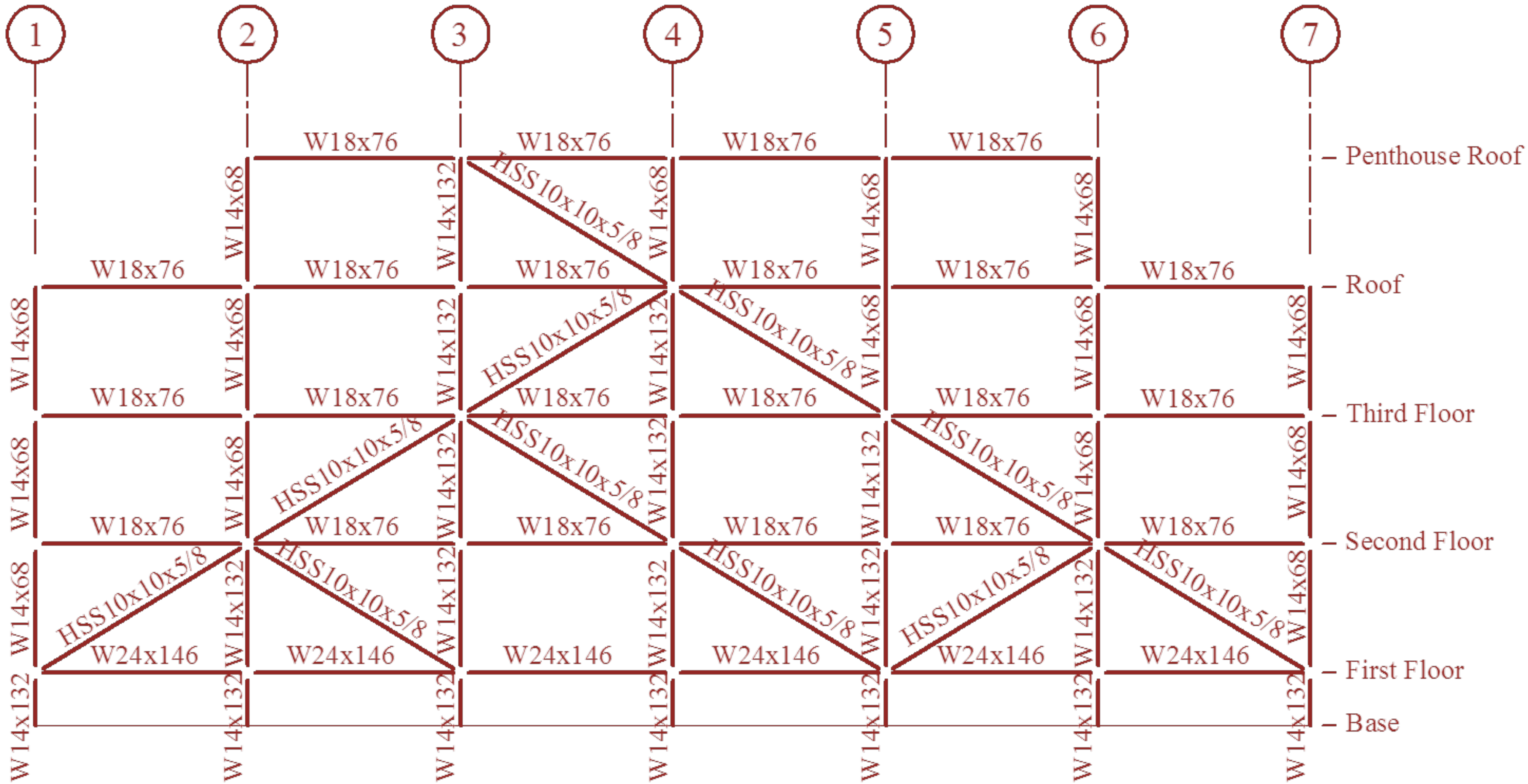
Emergency Operations Center Design Example

Framing on Line 4 – Preliminary Design



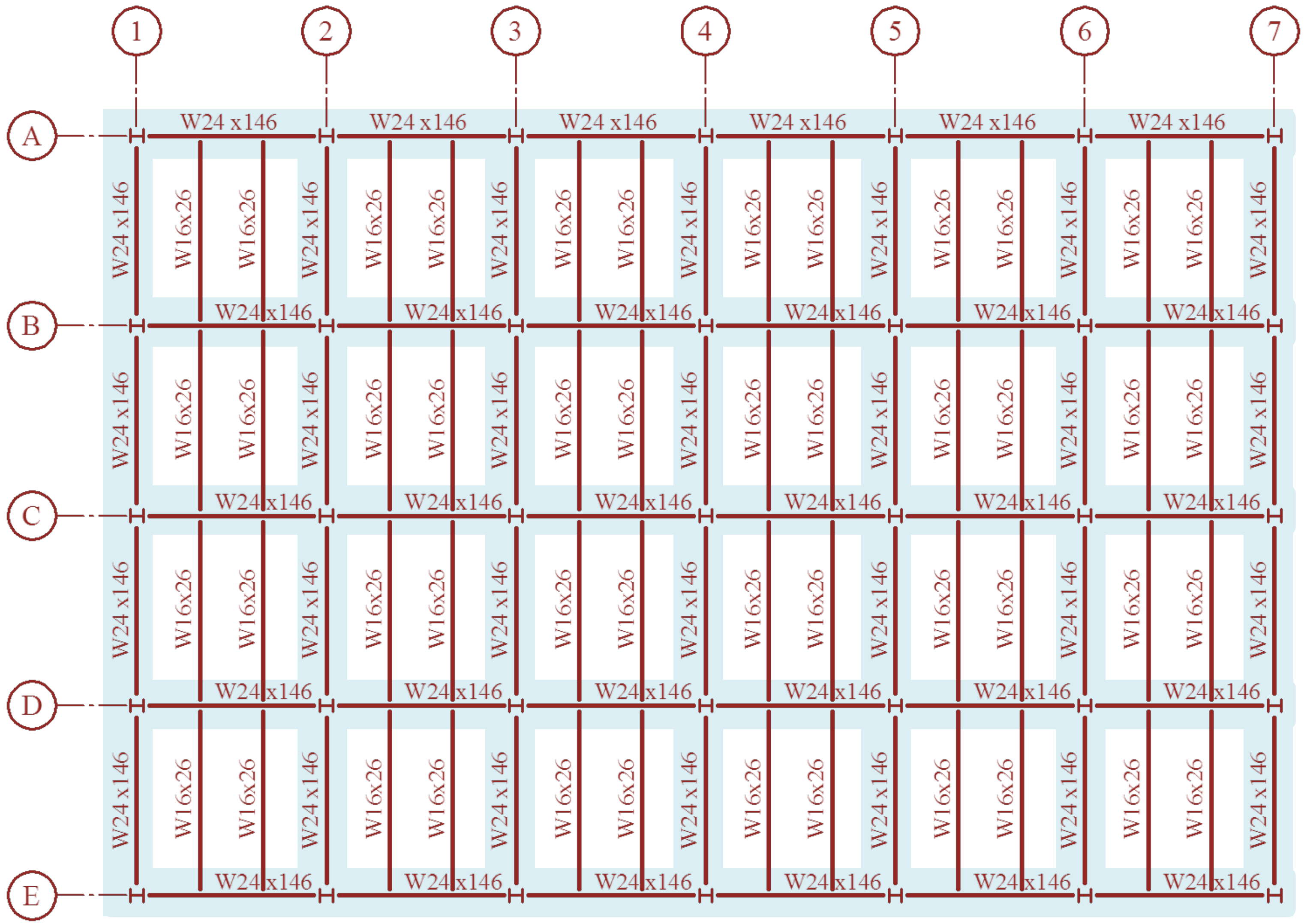
Emergency Operations Center Design Example

Framing on Lines B and D – Preliminary Design

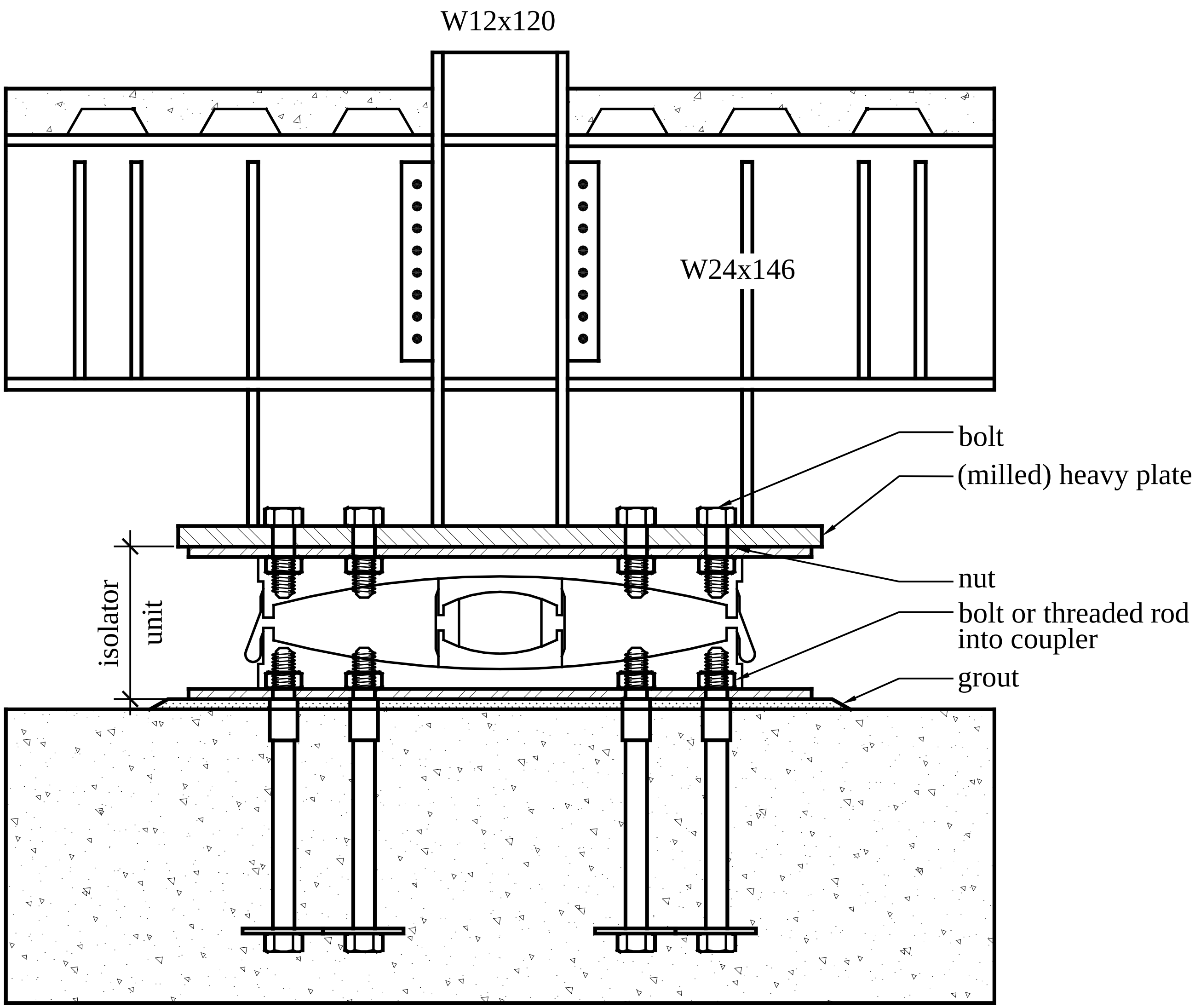


Emergency Operations Center Design Example

First-Floor Framing – Preliminary Design

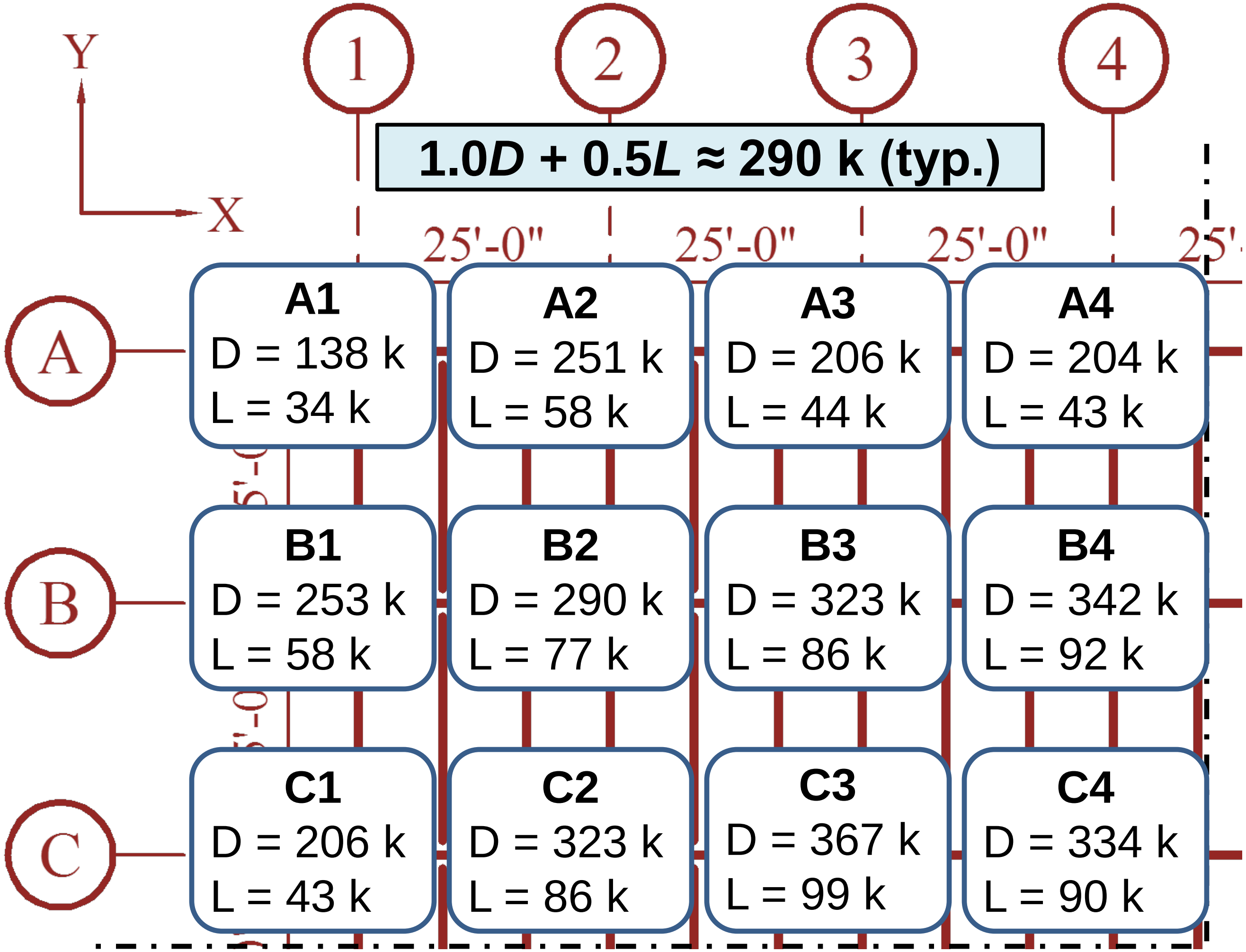


Emergency Operations Center Design Example
Typical Detail of Isolation System - Preliminary Design

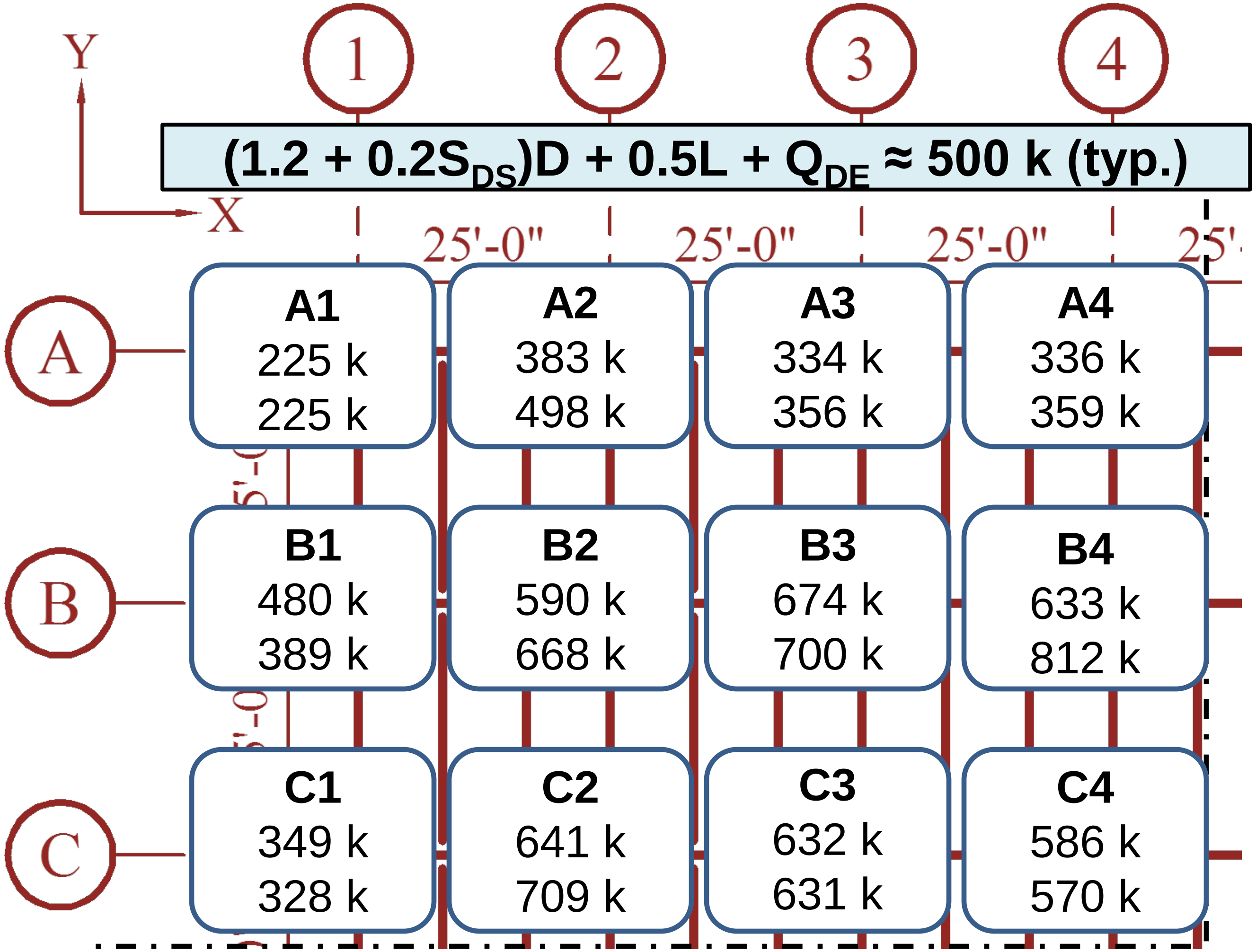


Emergency Operations Center Design Example

Typical Gravity (Dead/Live Load) Weight on Isolators

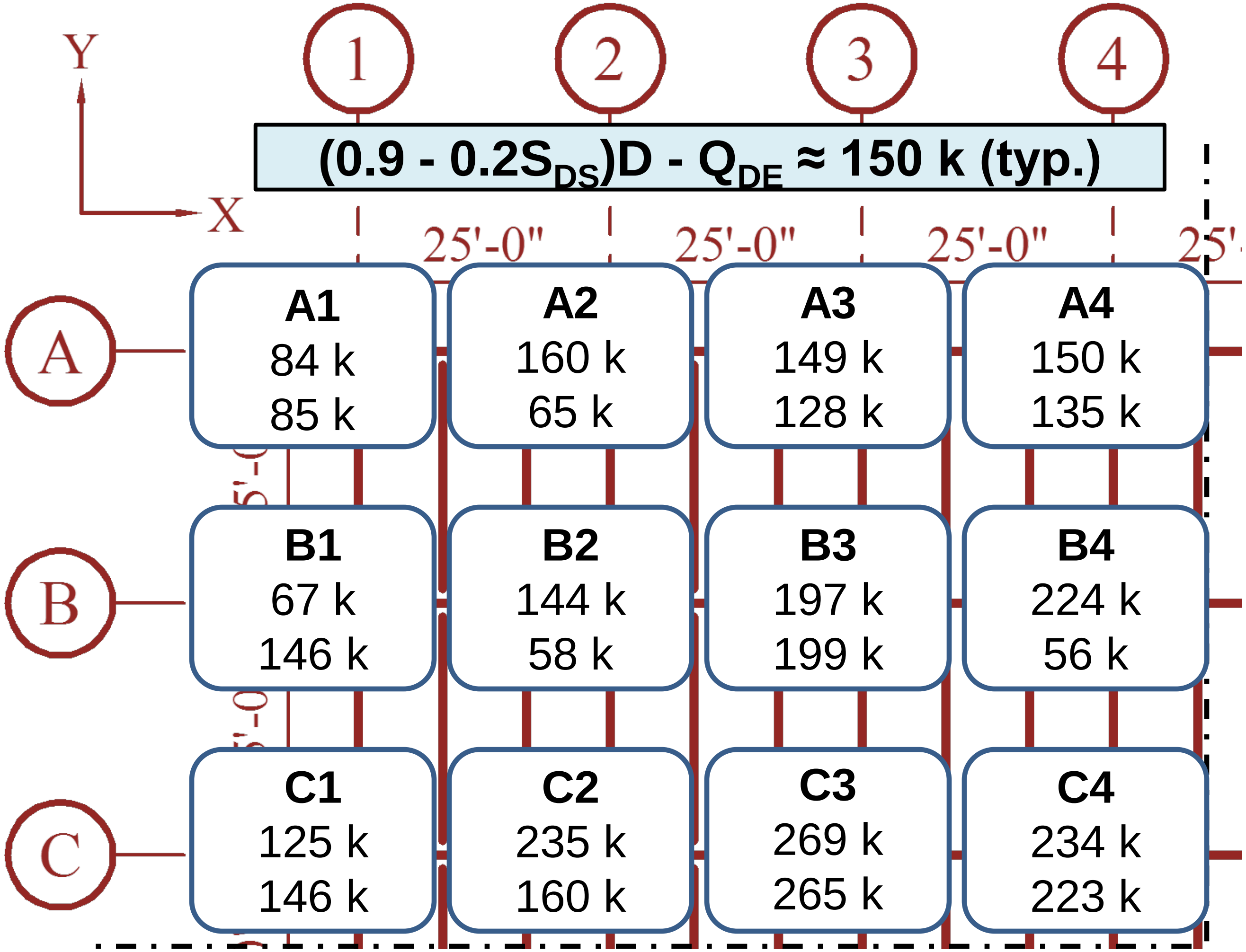


Emergency Operations Center Design Example
Maximum Downward Design Forces on Isolators



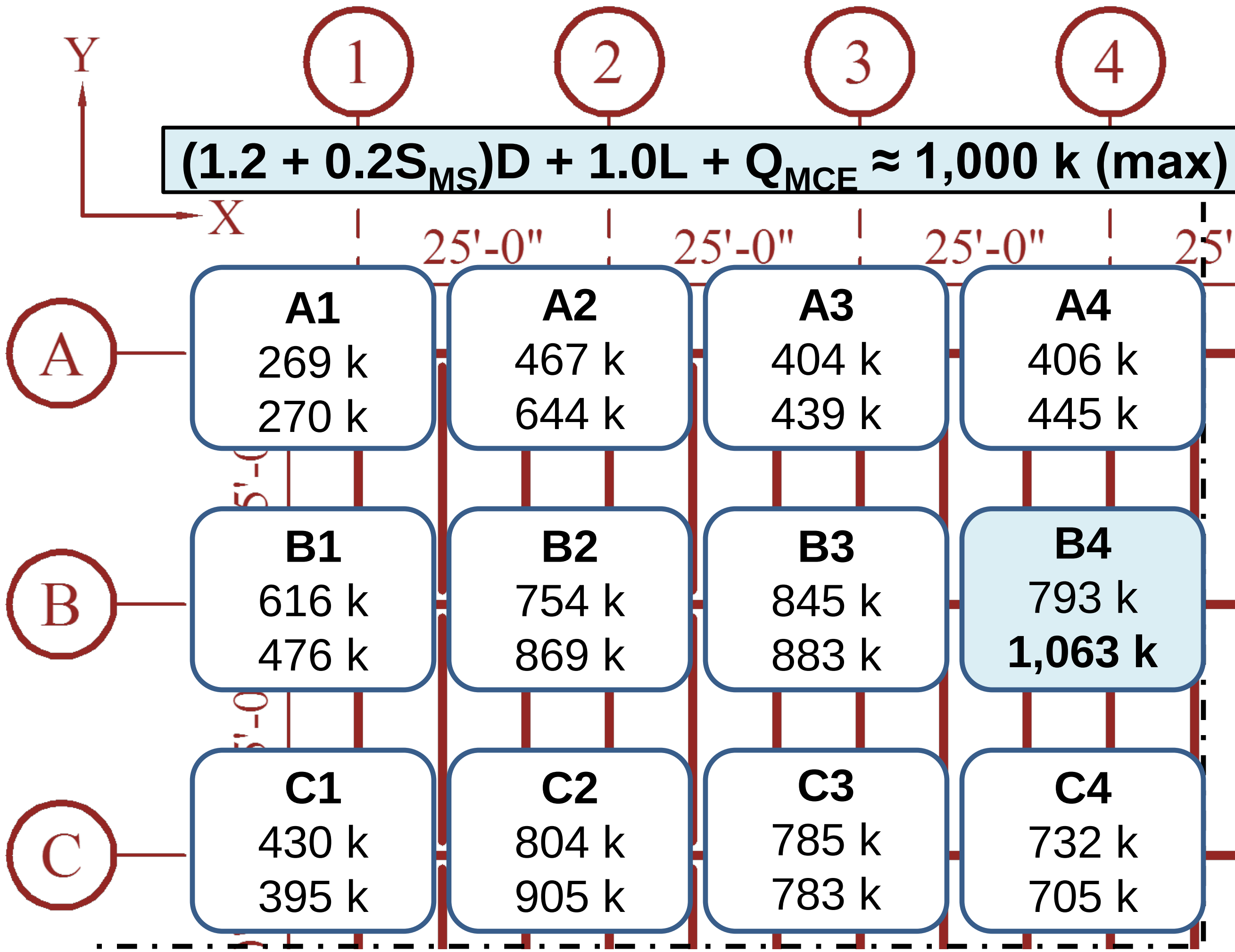
Emergency Operations Center Design Example

Minimum Downward Design Forces on Isolators



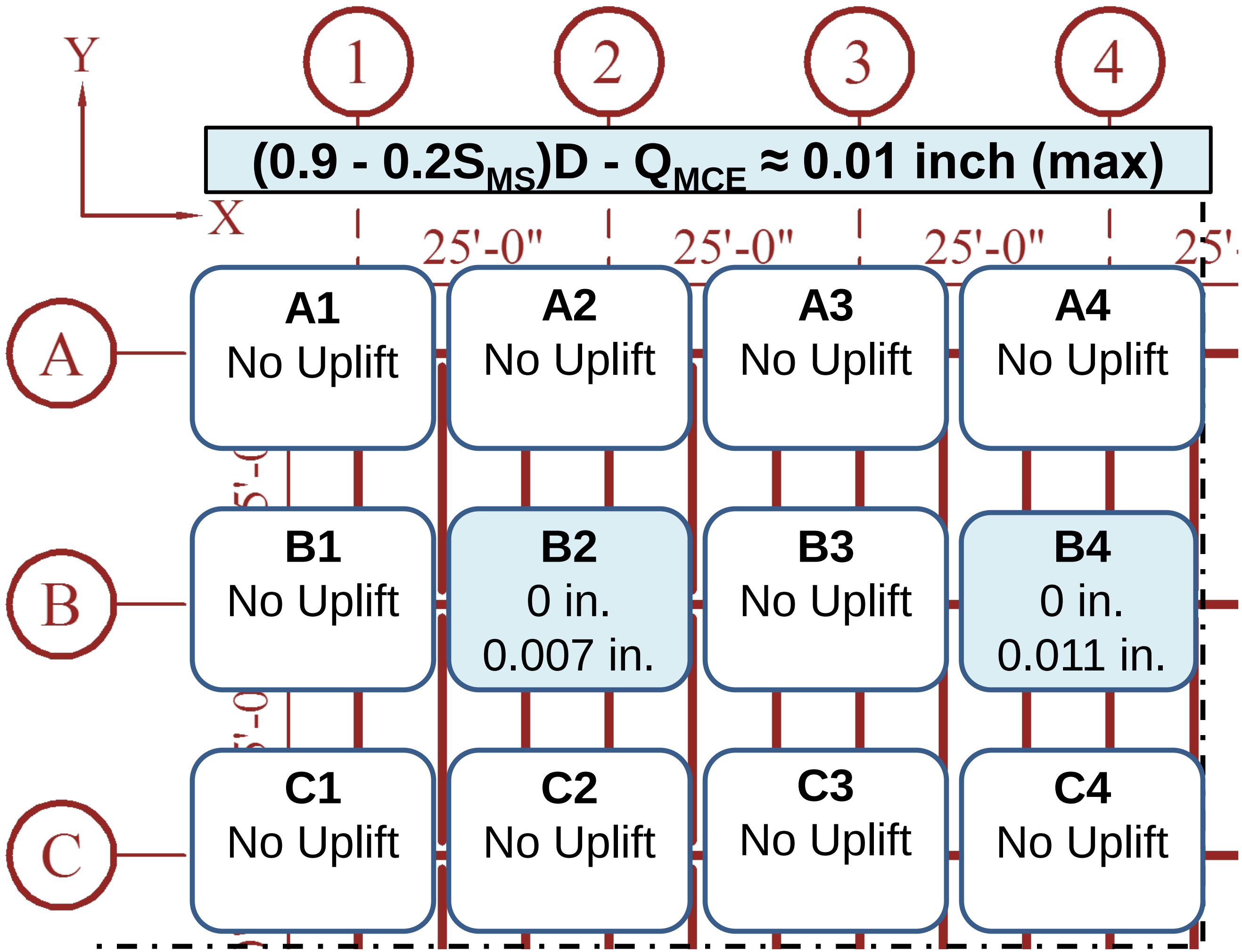
Emergency Operations Center Design Example

Maximum (Downward) MCE_R Forces on Isolators



Emergency Operations Center Design Example

Maximum MCE_R Uplift Displacement of Isolators

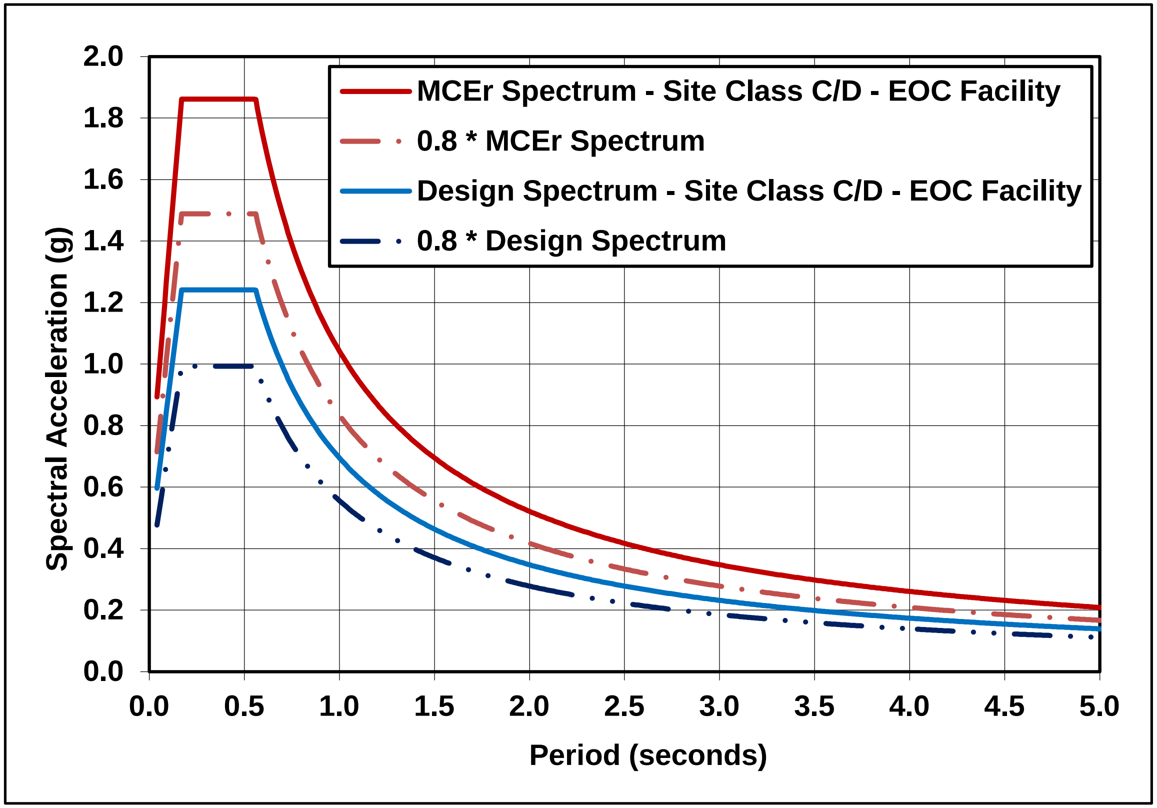


Emergency Operations Center Design Example
RHA Final Design (Design Verification)

- Dynamic analysis (RSA or RHA) is required for design of the EOC building since $S_1 \geq 0.60g$ and $T_M > 3.0s$
- RHA is <u>not</u> required for design of the EOC building since site conditions are not "soft" and the isolation system meets the criteria of Section 17.4.1.7, but is used in this example to:
  - Verify lateral ELF forces used for preliminary design of the structure above the isolation system
  - Calculate maximum displacements used for final design of the isolation system (and testing of individual isolator units)
  - Verify maximum forces used for preliminary design of the isolation system and foundations
  - Verify uplift displacements of individual isolator units

Emergency Operations Center Design Example
RHA Design Verification – Target Response Spectra

- Target design and MCE_R response spectra of this example use 100 percent of "Code" spectra in lieu of site-specific spectra required for design isolated structures located at sites with $S_1 \geq 0.6$ g (Section 11.4.7)



Emergency Operations Center Design Example
RHA Design Verification - Earthquake Record Selection

- Select earthquake ground motion records to match seismic source and site conditions of the EOC facility
  - Seismic source (dominant fault) information available from site hazard de-aggregation (https://geohazards.usgs.gov/deaggint/2008/)
  - Site conditions may be assumed (e.g., Site Class D) or determined by geotechnical study (i.e., $v_{s,30}$)
- EOC site seismic hazard dominated by the Hayward fault:
  - Fault type - Strike-slip
  - Characteristic magnitude – M7+
  - Fault Proximity – Within 6 km (near source)
- EOC site conditions:
  - Site Class – Site Class C/D ($v_{s,30}$ = 450 meters/sec.)

Emergency Operations Center Design Example
Selection of Earthquake Ground Motion Records

- Seven strike-slip records selected from the near-field (NF) and far-field (FF) record sets of FEMA P695 with mean properties:
  - Magnitude = M7.37
  - Distance to source = 5.2 km (JB)
  - Shear wave velocity, $v_{s,30}$ = 446 mps

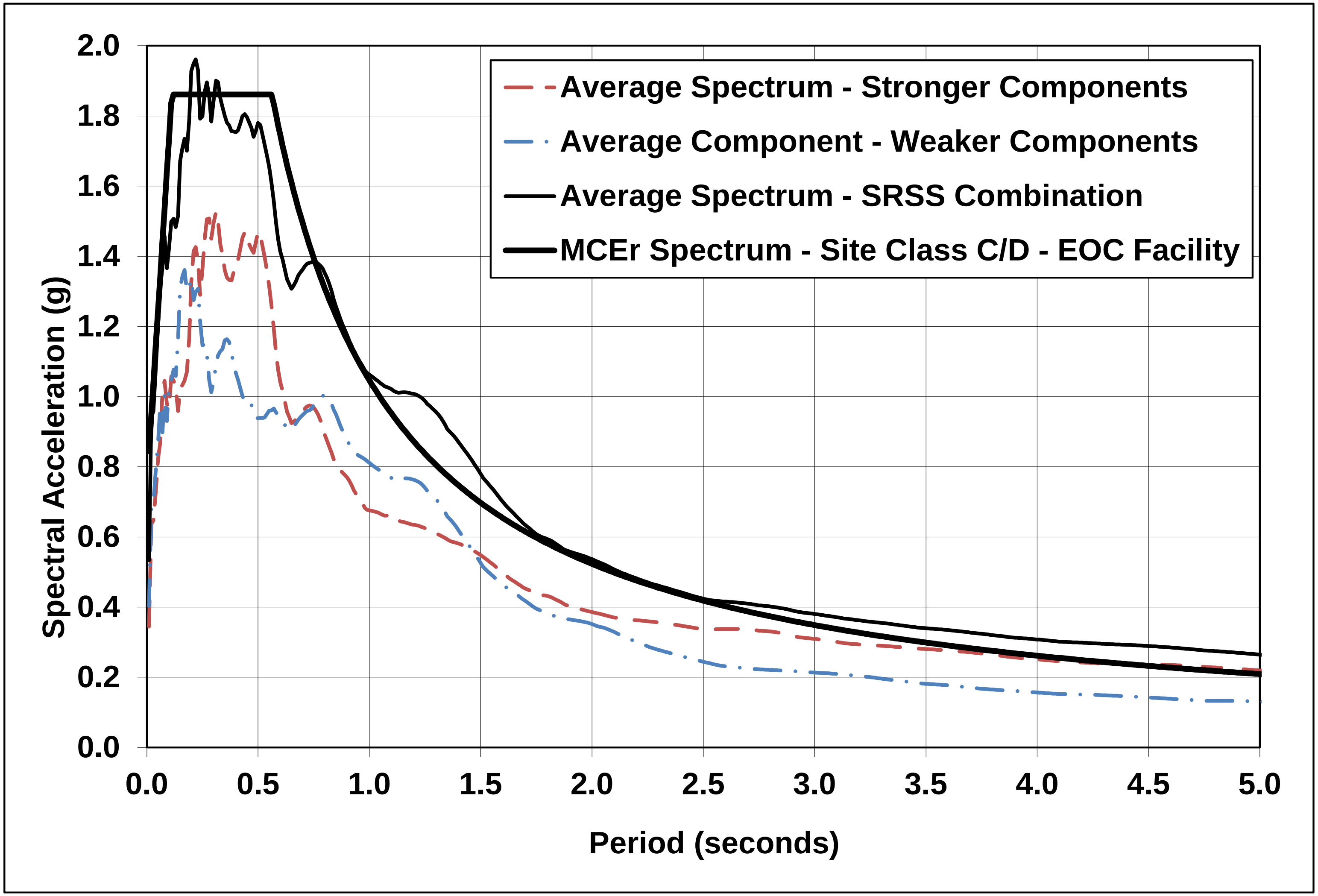
FEMA P695 Record ID No.	Earthquake			Source Characterisitcs				Site Conditions	
	Year	Name	Record Station	Mag. (M_w)	Distance D_f (km)		Fault Mechanism	Site Class	$v_{s,30}$ (m/sec.)
					JB	Rupture			
NF-8	1992	Landers	Lucerne	7.3	2.2	15.4	Strike-slip	C	685
FF-10	1999	Kocaeli,	Arcelik	7.5	10.6	13.5	Strike-slip	C	523
NF-25	1999	Kocaeli	Yarimca	7.5	1.4	5.3	Strike-slip	D	297
FF-3	1999	Duzce	Bolu	7.1	12.0	12.0	Strike-slip	D	326
NF-14	1999	Duzce	Duzce	7.1	0.0	6.6	Strike-slip	D	276
FF-4	1999	Hector Mine	Hector	7.1	10.4	11.7	Strike-slip	C	685
NF-28	2002	Denali	TAPS PS#10	7.9	0.2	3.8	Strike-slip	D	329
Mean Property of Seven Records				7.37	5.2	9.8			446

Emergency Operations Center Design Example
Scaling of Earthquake Ground Motion Records

- Earthquake ground motion records oriented to have a common axis of stronger shaking response (at long periods) and scaled:
  - Average spectrum of SRSS combination of scaled records envelops MCE_R spectrum from 1.75 seconds (0.5 T_D) to 4.9 seconds (1.25 T_M)
  - Average spectrum of the stronger components is comparable to MCE_R spectrum at response periods of interest (e.g., 3.9 seconds for MCE_R analysis)

FEMA P695 Record ID No.	Earthquake			Normalization and Scaling Factors			
	Year	Name	Record Station	PGV_{PEER} (cm/s)	PGV Normal. Factor	Oakland Site	
						DE	MCE
NF-8	1992	Landers	Lucerne	97.2	0.60	0.62	0.94
FF-10	1999	Kocaeli,	Arcelik	27.4	2.13	2.21	3.32
NF-25	1999	Kocaeli	Yarimca	62.4	0.93	0.97	1.46
FF-3	1999	Duzce	Bolu	59.2	0.99	1.02	1.54
NF-14	1999	Duzce	Duzce	69.6	0.84	0.87	1.31
FF-4	1999	Hector Mine	Hector	34.1	1.71	1.78	2.67
NF-28	2002	Denali	TAPS PS#10	98.5	0.59	0.62	0.92
Median Property of Seven Records				58.3	1.00	1.04	1.56

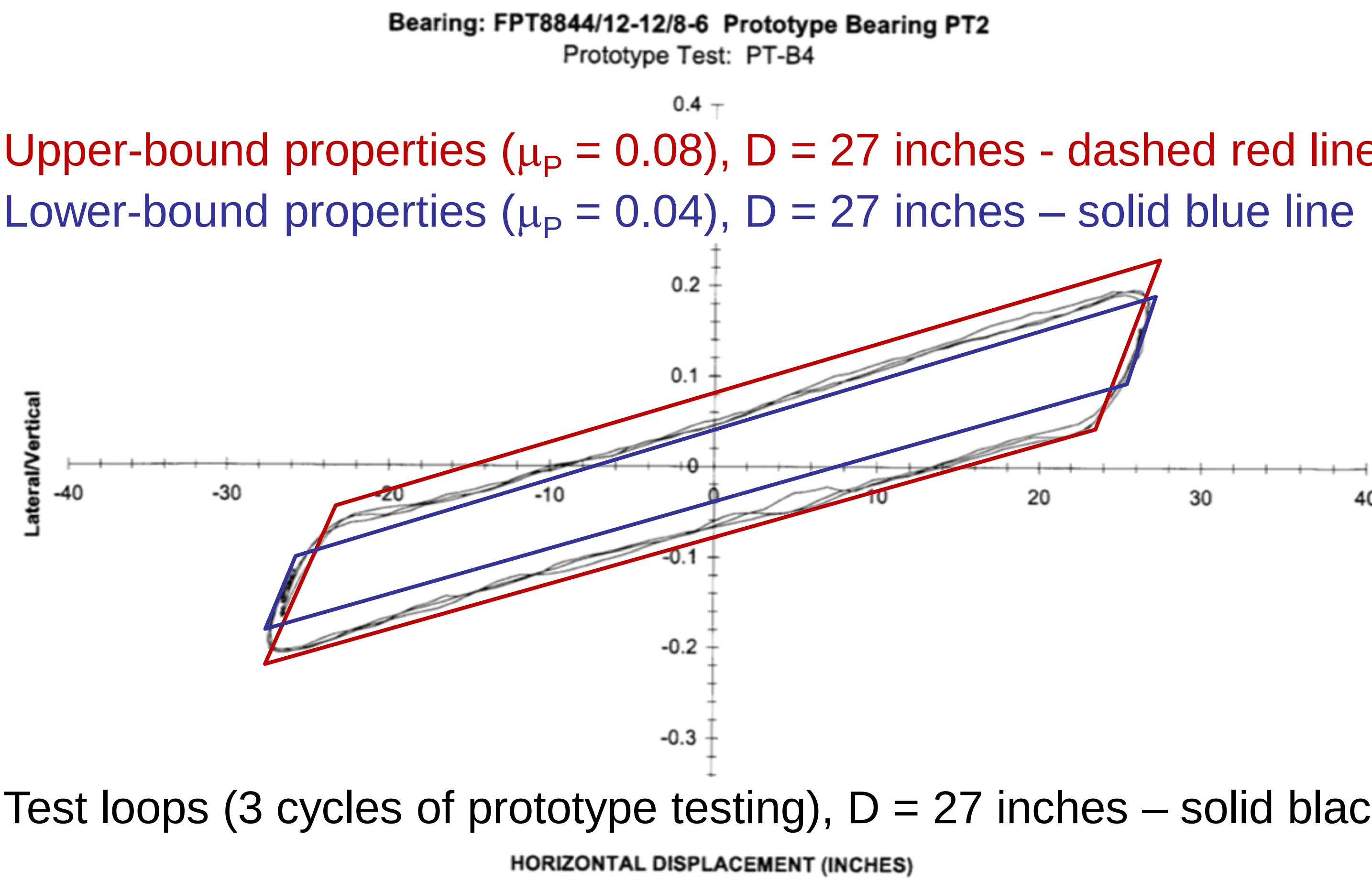
Comparison of Average Spectra of Scaled Records and Target MCE_R Spectrum



Emergency Operations Center Design Example
RHA Design Verification – Modeling

- Isolated Structure Modeling Requirements:
  - Linear elastic model of "essentially elastic" superstructure
  - Explicit nonlinear modeling of isolator units
- Isolation System Modeling Requirements:
  - Properties developed and verified by prototype test (same as ELF)
  - Account for spatial distribution of isolators
  - Consider translation in both horizontal direction (3-dimensional)
  - Access overturning/uplift forces on individual isolator units
  - Account for the effects of vertical load, etc., on isolators
- ETABS Model
  - Same model as that used for pushover (with ELF lateral forces)
  - Isolators modeled as bi-linear elements (representing upper-bound and lower-bound properties of bearing stiffness)

Emergency Operations Center Design Example
Comparison of Modeled and Tested Hysteresis Loops - RHA



Avg. Vert. Load (kips)	383
Max. Vert. Load (kips)	467
Min. Vert. Load (kips)	304
Peak Velocity (in/sec)	4.8

Cycle	Keff (kip/in/kip.)	EDC (kip-in/kip.)	Friction	Damping
1 st.	0.00773	6.5466	0.063	19.9%
2nd	0.00767	6.1841	0.059	19.0%
3rd.	0.00766	6.1513	0.059	18.9%
Avg.	0.00769	6.2940	0.061	19.3%

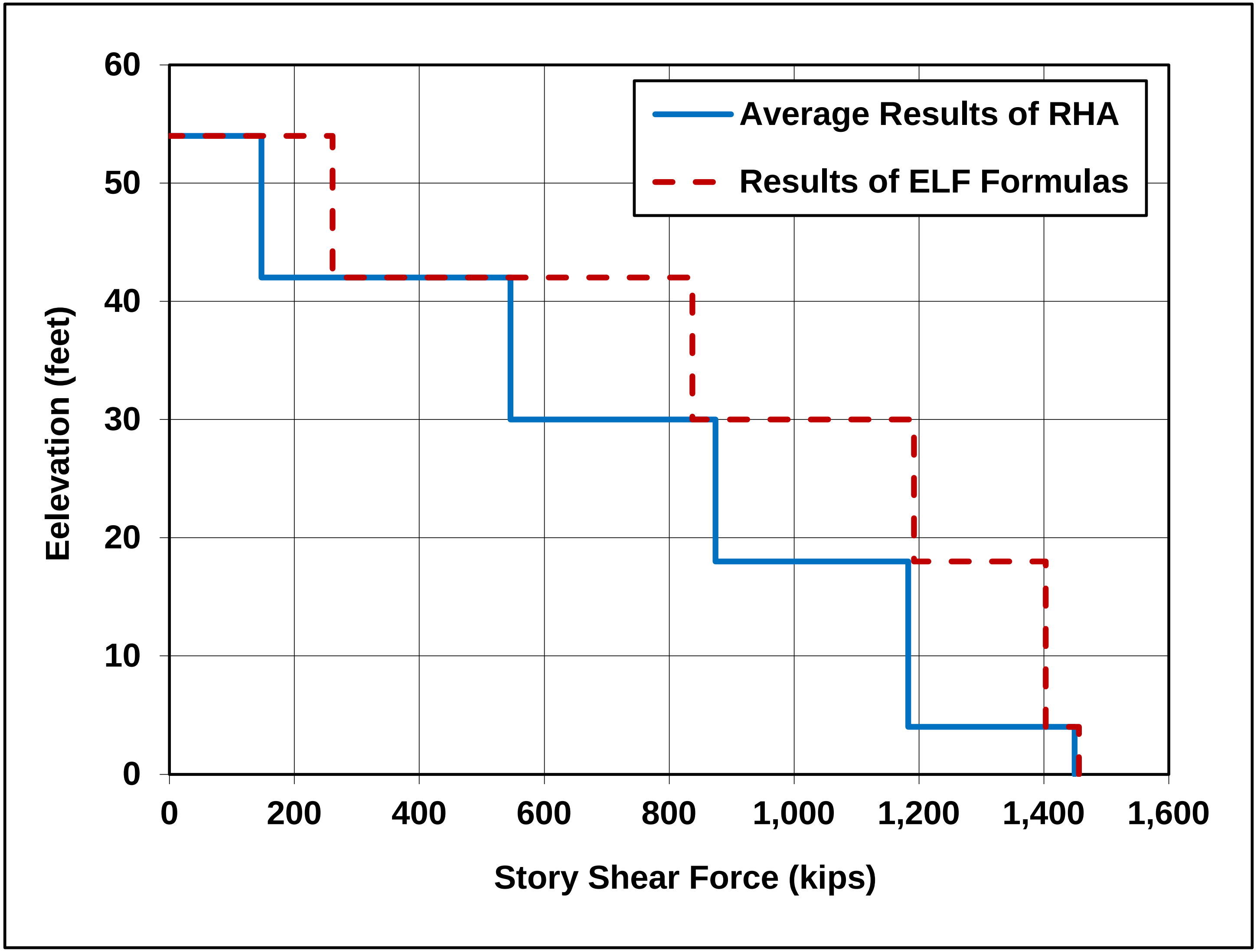
Emergency Operations Center Design Example

Design Verification - RHA

Response Parameter	Method of Analysis		
	ELF Formulas	RHA - Average of Seven Records	
		X-axis Direction	Y-axis Direction
Design Earthquake - Story Shear (kips)			
Penthouse	261	150	147
3rd Story	837	546	531
2nd Story	1,192	874	855
1st Story	1,403	1,183	1173
V_b (Isolators)	1,456	1,440	1449

Emergency Operations Center Design Example

Design Verification - RHA



Emergency Operations Center Design Example

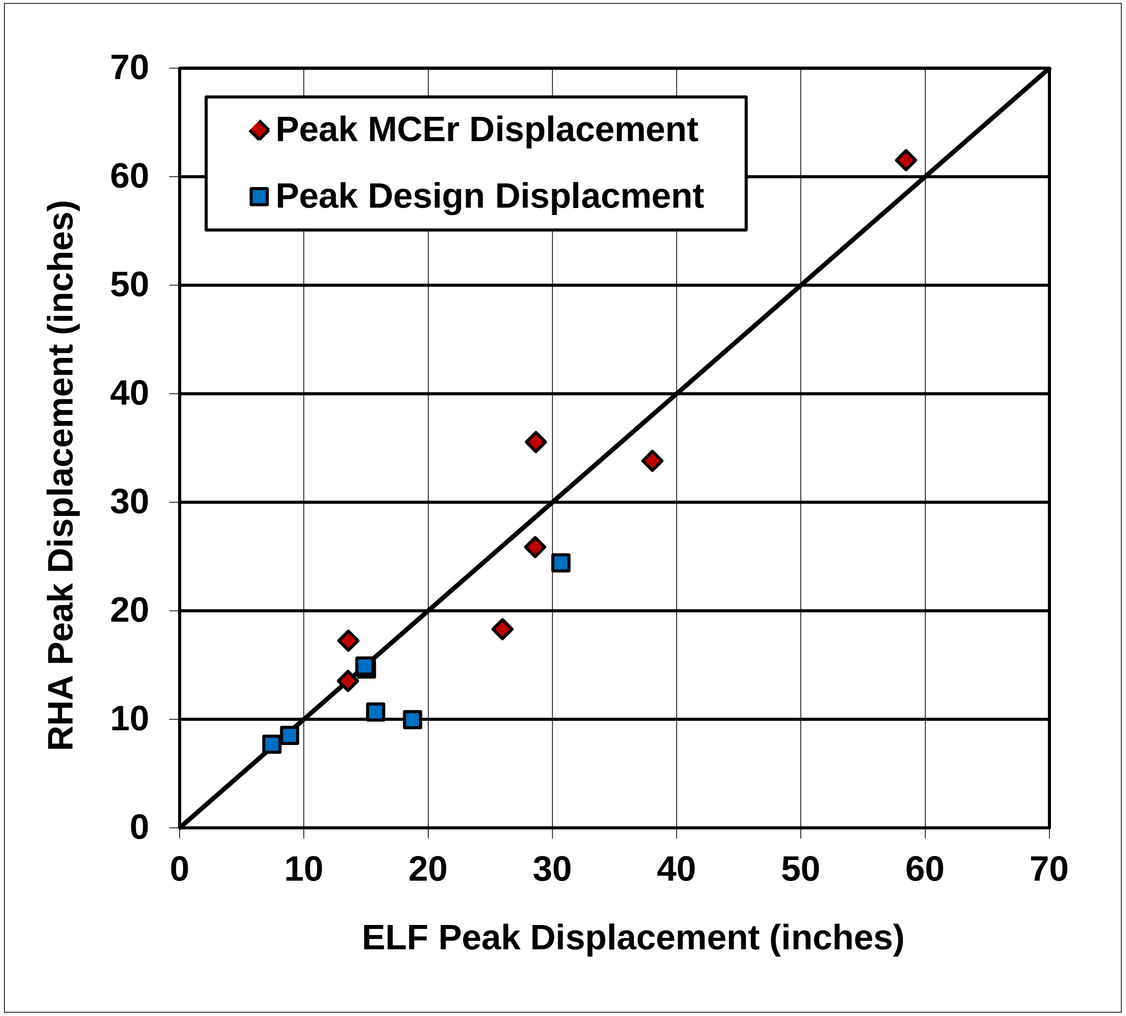
Design Verification - RHA

Response Parameter	Method of Analysis		
	ELF Formulas	RHA - Average of Seven Records	
		Maximum (X,Y)	X-Y Plane
Design Earthquake - Isolation System Displacement (inches)			
Design (Center)	16.0	15.0	15.9
Total (Corner)	17.6	16.5	17.5
Uplift	NA	No uplift (all records)	
MCE_R - Isolation System Displacement (inches)			
MCE_R (Center)	30.9	28.2	29.6
Total (Corner)	34.0	31.1	32.5
Uplift	NA	Less than 0.01 in. (2/7 records)	

Emergency Operations Center Design Example
Comparison of ELF and RHA Methods – Individual Records

Response Parameter	Seven Scaled Earthquake Ground Motion Records (FEMA P-695 ID No.)							Average Value
	NF-8	FF-10	NF-25	FF-3	NF-14	FF-4	NF-28	
RHA - Peak Isolation System Displacement - Design Earthquake (inches)								
X Direction	14.9	18.3	30.5	7.5	14.2	5.8	13.6	15.0
Y Direction	3.2	4.9	11.3	7.1	9.5	5.6	7.7	7.1
X-Y Direction	15.0	18.8	30.7	8.9	14.9	7.4	15.8	15.9
ELF Estimate of Peak Isolation System Displacement - Design Earthquake (inches) - T_D = 3.5 seconds								
S_{aD} [T_D] (g)	0.182	0.124	0.305	0.106	0.186	0.096	0.133	0.187
S_{dD} [T_D] (in.)	21.9	14.9	36.6	12.7	22.3	11.5	16.0	22.4
$D_D = S_{dM}/B_D$	14.6	9.9	24.4	8.5	14.9	7.7	10.6	15.0
RHA_ Peak Isolation System Displacement - MCE (inches)								
X Direction	28.6	36.5	58.1	11.4	27.3	13.0	22.7	28.2
Y Direction	4.5	9.7	21.8	10.3	18.8	9.0	13.2	12.5
X-Y Direction	28.7	38.1	58.5	13.6	28.6	13.6	26.0	29.6
ELF Estimate of Peak Isolation System Displacement - MCE (inches) - T_M = 3.9 seconds								
S_{aM} [T_M] (g)	0.310	0.295	0.536	0.118	0.225	0.150	0.159	0.256
S_{dM} [T_M] (in.)	46.2	43.9	79.9	17.6	33.6	22.4	23.8	38.2
$D_M = S_{dM}/B_D$	35.5	33.8	61.5	13.5	25.8	17.2	18.3	29.4

Emergency Operations Center Design Example
Comparison of ELF and RHA Methods – Individual Records



Prototype Testing – Number and Type of Test Specimens

- Two of Each Isolator Type and Size. Prototype tests shall be performed separately on two full-sized specimens (or sets of specimens, as appropriate) of each predominant type and size of isolator unit of the isolation system
- Wind Restraint System. Test specimens shall include the wind-restraint system as well as individual isolator units is such systems are used in the design
- Prototype Test Specimens Not Permitted for Construction. Test specimens shall not be used for construction unless accepted by the registered design professional
- (Make) Use of Prior Prototype Testing. Prototype testing may be based on prior prototype testing of the same type and size of isolator unit for comparable test loads

Emergency Operations Center Design Example

Prototype Testing – Sequence and Cycles

No. of Cycles	*Standard* Criteria		Example EOC Criteria	
	Vertical Load	Lateral Load	Vertical Load	Lateral Load
Cyclic Load Tests to Establish Effective Stiffness and Damping (Standard Sec. 17.8.2.2, w/o Item 1)				
3 cycles	Typical	$0.25D_D$, $0.5D_D$, $1.0D_D$, and $1.0D_M$	290 kips	4, 8, 16 and 30 in.
3 cycles	Upper-bound		500 kips	4, 8, 16 and 30 in.
3 cycles	Lower-bound		150 kips	4, 8, 16 and 30 in.
3 cycles	Typical	$1.0D_{TM}$	290 kips	32.5 in.
Cyclic Load Tests of Durability (Standard Sec. 17.8.2.2)				
$30S_{D1}/S_{DS}B_D$ ≥10 cycles	Typical	$1.0D_{TD}$	290 kips	17.5 in.
Static Load Test of Isolator Stability (Standard Sec. 17.8.2.5)				
N/A	Maximum	$1.0D_{TM}$	1,000 kips	32.5 in.
N/A	Minimum	$1.0D_{TM}$	0.1 in. of uplift	32.5 in.

Emergency Operations Center Design Example

Prototype Testing – Effective Properties of Isolator Units

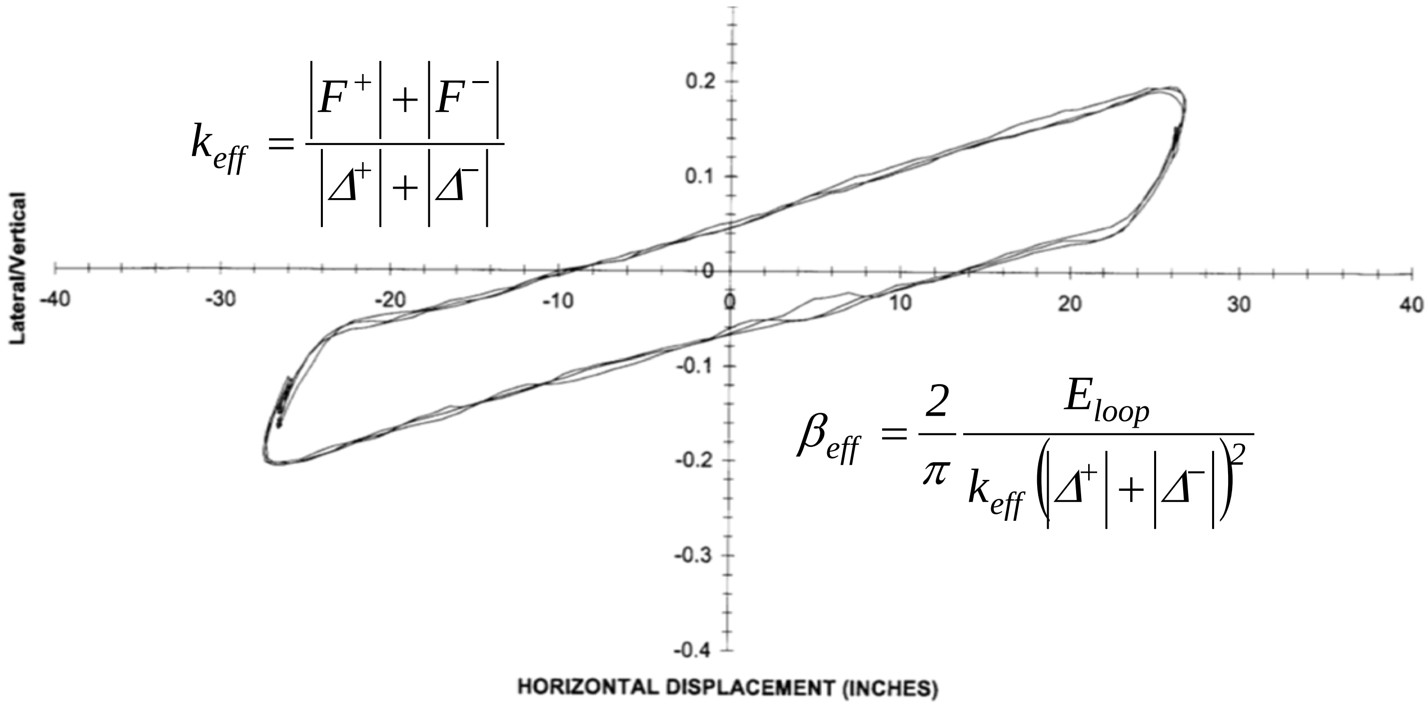
Bearing: FPT8844/12-12/8-6 Prototype Bearing PT2

Prototype Test: PT-B4

- Effective stiffness, k_{eff}, and effective damping, β_{eff}, of each prototype isolator unit is calculated for each cycle of test loading:

$$k_{eff} = \frac{|F^+| + |F^-|}{|\Delta^+| + |\Delta^-|}$$

$$\beta_{eff} = \frac{2}{\pi} \frac{E_{loop}}{k_{eff}\left(|\Delta^+| + |\Delta^-|\right)^2}$$



		Cycle	Keff (kip/in/kip.)	EDC (kip-in/kip.)	Friction	Damping
Avg. Vert. Load (kips)	383					
Max. Vert. Load (kips)	467	1 st.	0.00773	6.5466	0.063	19.9%
Min. Vert. Load (kips)	304	2nd	0.00767	6.1841	0.059	19.0%
Peak Velocity (in/sec)	4.8	3rd.	0.00766	6.1513	0.059	18.9%
		Avg.	0.00769	6.2940	0.061	19.3%

Prototype Testing – Maximum and Minimum Effective Properties of the Isolation System at the Design Displacement

Total maximum force at positive D_D (maximum of 3 cycles at a given vertical load level)

$$k_{D\,max} = \frac{\sum \left|F_D^+\right|_{max} + \sum \left|F_D^-\right|_{max}}{2D_D}$$

Maximum effective stiffness
(before modification to account for effects of aging, contamination, etc.)

$$k_{D\,min} = \frac{\sum \left|F_D^+\right|_{min} + \sum \left|F_D^-\right|_{min}}{2D_D}$$

Minimum effective stiffness
(before modification to account for effects of aging, contamination, etc.)

Total loop area at $1.0D_D$ (minimum of 3 cycles at a given load level)

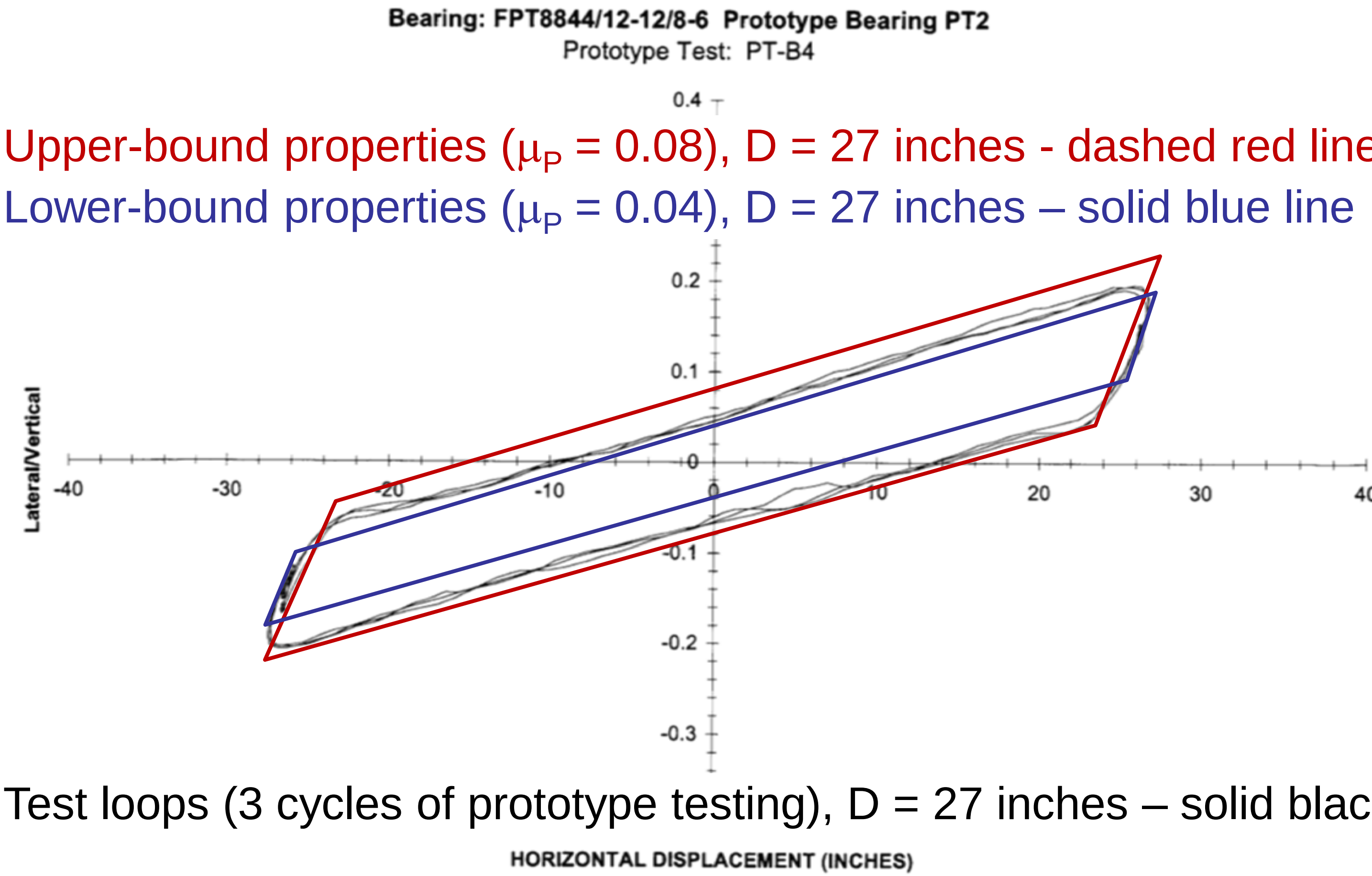
$$\beta_D = \frac{1}{2\pi} \frac{\sum E_D}{k_{D\,max} D_D^2}$$

Effective damping
(before modification to account for effects of aging, contamination, etc.)

Modeling and Analysis
Comparison of Modeled and Tested Hysteresis Loops

Upper-bound properties (μ_P = 0.08), D = 27 inches - dashed red line

Lower-bound properties (μ_P = 0.04), D = 27 inches – solid blue line



Test loops (3 cycles of prototype testing), D = 27 inches – solid black

		Cycle	Keff (kip/in/kip.)	EDC (kip-in/kip.)	Friction	Damping
Avg. Vert. Load (kips)	383					
Max. Vert. Load (kips)	467	1 st.	0.00773	6.5466	0.063	19.9%
Min. Vert. Load (kips)	304	2nd	0.00767	6.1841	0.059	19.0%
Peak Velocity (in/sec)	4.8	3rd.	0.00766	6.1513	0.059	18.9%
		Avg.	0.00769	6.2940	0.061	19.3%

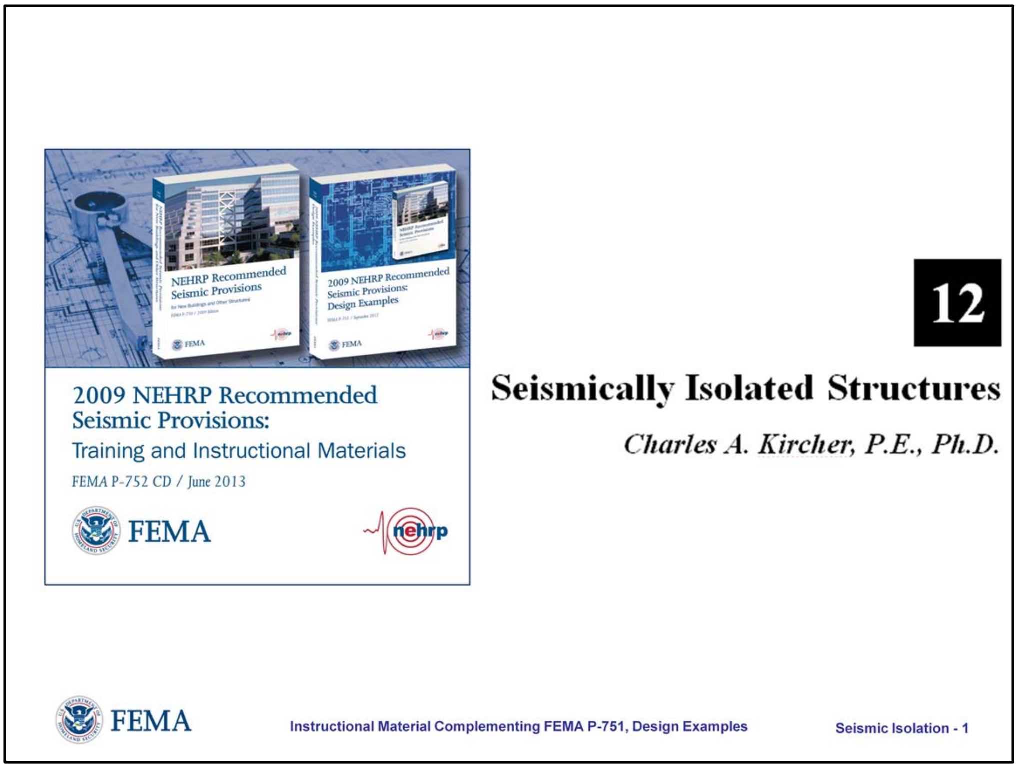
Prototype Testing – Acceptance Criteria of Test Specimens

- Cyclic-load tests to establish effective stiffness and damping:
  - Force-deflection plots have positive incremental restoring force capacity
  - For each increment of test displacement and vertical load:
    - For each test specimen, the effective stiffness at each of the 3 cycles of test loading is within 15 percent of the average stiffness over the 3 cycles of test load
    - For each of two test specimens (of common type and size), the effective stiffness of one specimen is within 15 percent of the effective stiffness of the other (at each of the 3 cycles of test loading, and on average)
- Cyclic-load tests to check durability – for each test specimen:
  - There is no more than 20 percent change in effective stiffness
  - There is no more than a 20 percent reduction in effective damping
- Static-load tests to verify isolator unit stability
  - All test specimens remain stable (for maximum MCE_R loads)

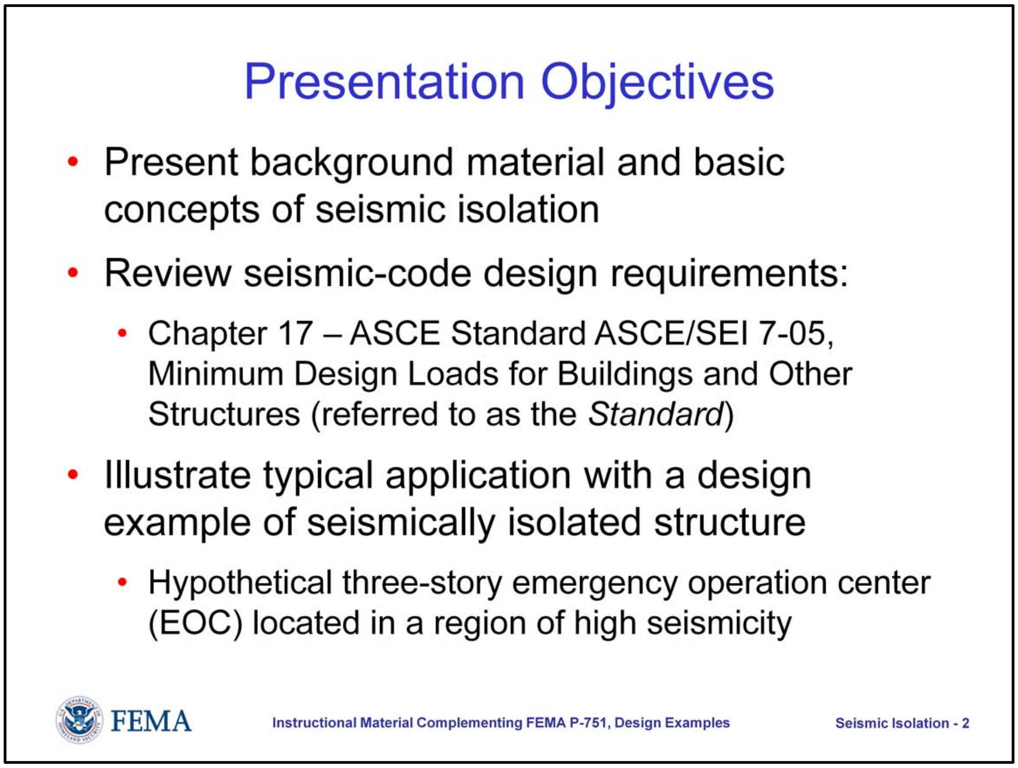
Emergency Operations Center Design Example
Prototype Testing of Double-Concave FPS Bearing (FPT8844/12-12/8-6)

Emergency Operations Center Design Example
Post-Test Inspection of Double-Concave FPS Bearing (FPT8844/12-12/8-6)

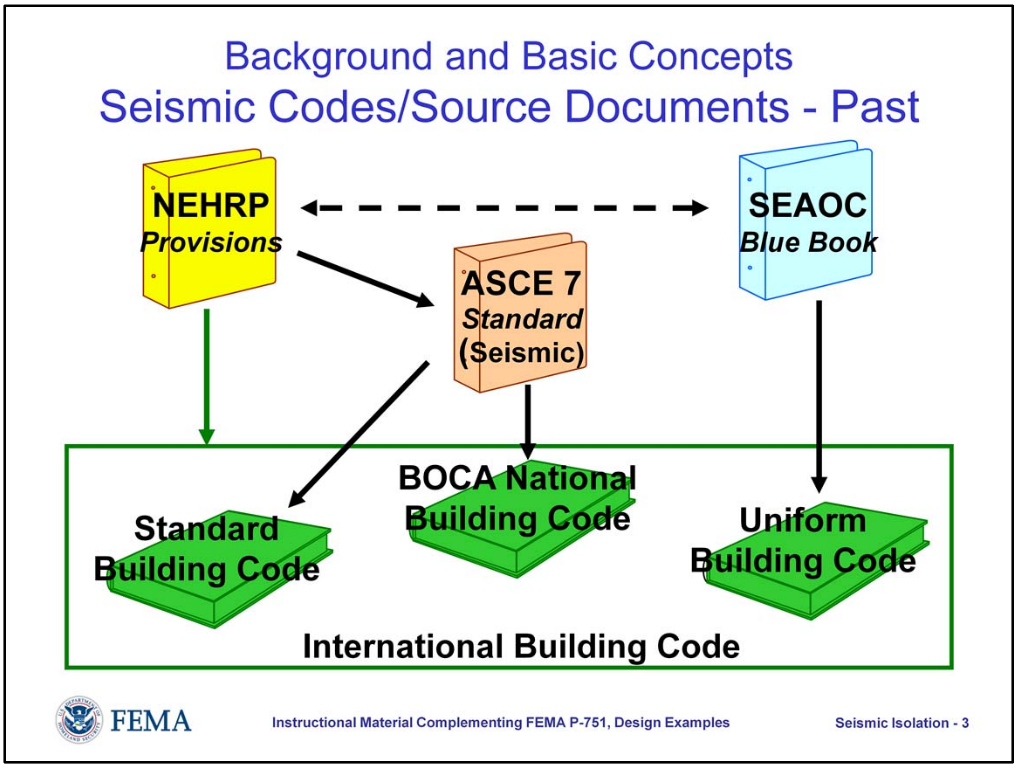
Questions



This set of instructional slides presents the design example and background material for "seismically isolated structures," Chapter 12, of FEMA P-751, *2009 NEHRP Recommended Seismic Provisions: Design Examples*.

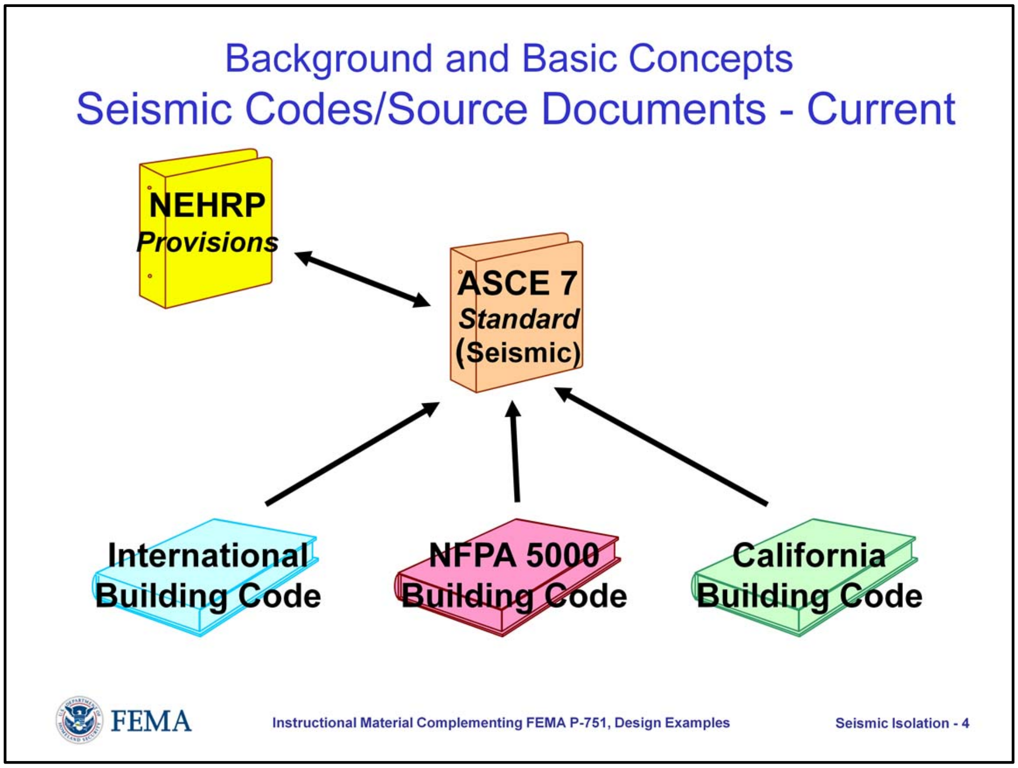


The three primary objectives of this instructional presentation of Chapter 12 material are: (1) to provide background on seismic isolation, basic concepts and analysis methods, (2) to review the seismic-code design requirements for seismically isolated structures (Chapter 17 of ASCE 7-05, referred to as the *Standard*), and (3) to illustrate a typical application seismic-code requirements with an example design of a hypothetical seismically-isolated 3-story emergency operation center located in a region of high seismicity. In the example, seismic loads are based on the new “risk-targeted” seismic design values of the 2009 NEHRP *Provisions*. Note. The most current version of ASCE 7 is ASCE 7-10 which adopted the new “risk-targeted” ground motions of 2009 NEHRP *Provisions* with only slight editorial changes, and did not incorporate substantive changes to Chapter 17 of ASCE 7-05. Thus, the material presented in these slides applies equally well to the design requirements of Chapter 17 of ASCE 7-10 for seismically isolated structures.



Initial development of design requirements for base-isolated buildings began with ad hoc groups of the Structural Engineers Association of California (SEAOC). These requirements were used by the California Office of Statewide Planning and Development (OSHPD) for regulation of first base-isolated hospital in California (University of Southern California Teaching Hospital) and subsequently adopted by the 1990 SEAOC Blue Book and as a non-mandatory appendix of the 1991 Uniform Building Code (1991 UBC). At that time, the SEAOC Blue Book served as the role model for the UBC, the model building code with the most up-to-date and widely respected seismic design requirements. In the 1990's, the design requirements for seismically-isolated structures were adopted as a mandatory section of the UBC and as a new chapter of the NEHRP Provisions. (Click).

Around the year 2000, the three major model building codes (SBC, BOCA and UBC) merged to form the new International Building Code (IBC) with seismic design requirements taken from the NEHRP Provisions (which were also adopted and incorporated into the American Society of Civil Engineers Standard, ASCE 7.



Today, model building codes (e.g., national model codes such as the IBC, or regional derivatives, such as the California Building Code, CBC) adopt by reference the seismic design requirements of ASCE 7 which are based on the NEHRP Provisions. As such, the design requirements for seismically isolated structures described in Chapter 12 of FEMA P-751 are taken from ASCE 7 (referred to simply as the *Standard*). The most current version of the *Standard*, ASCE 7-10, has been adopted by the 2012 IBC (by reference). Most jurisdictions and regulatory authorities in the United States have (or will) adopt the 2012 IBC (or regional derivatives thereof).

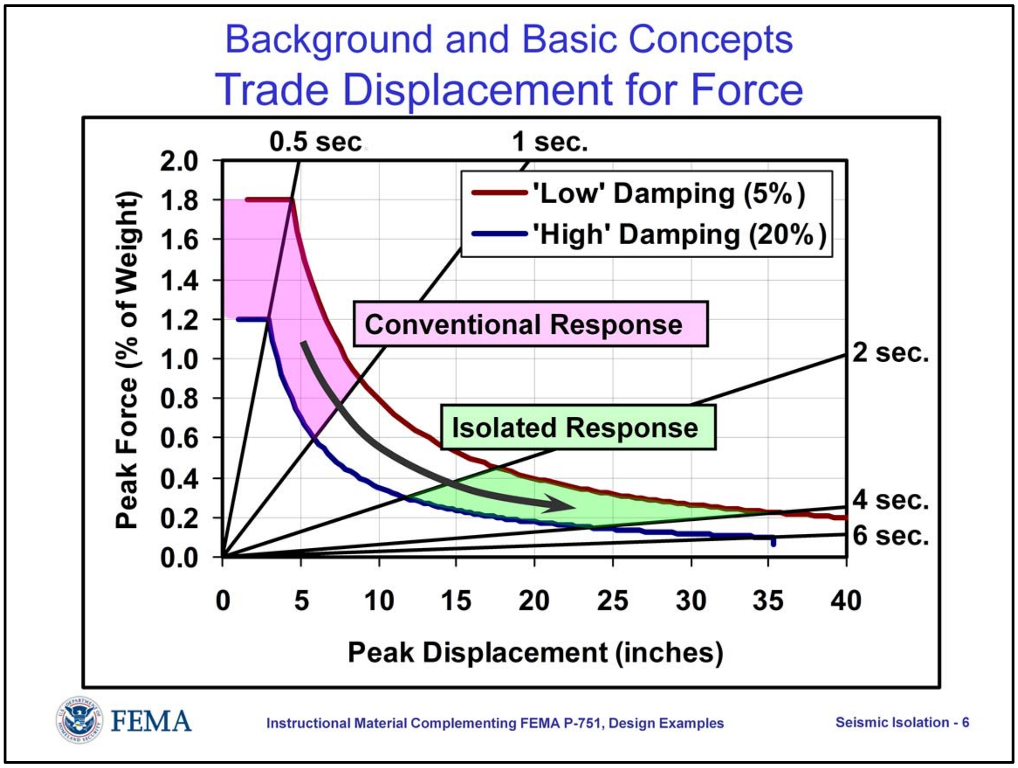
Background and Basic Concepts
Earthquake Response Modification

- De-couple structure above the isolation interface from potential damaging earthquake ground motions
- De-couple structure from earthquake ground motions by increasing period of the isolated structure to several times the period of the same structure on a fixed base
  - Trade displacement (of the isolation system) for force (in the structure above the isolation system)

FEMA Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 5

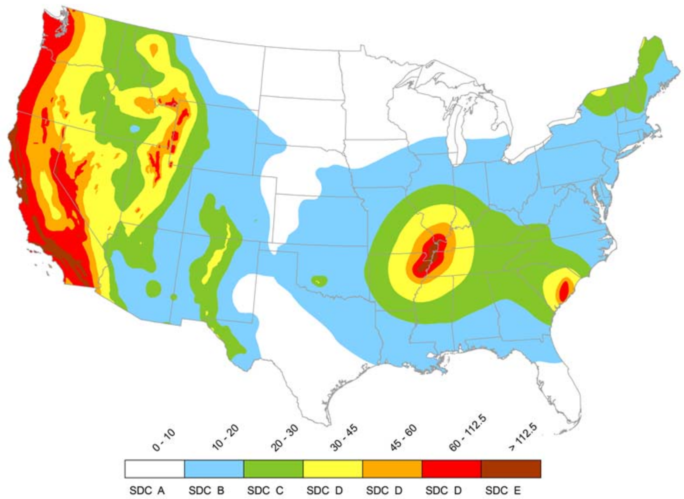
The basic concept of seismic isolation (also referred to as base isolation) is to "de-couple" the "superstructure" (structure above the isolation interface) from potentially damaging ground motions by adding "seismic isolators" which support the structure above while permitting large relative horizontal displacement of the structure in an earthquake. Note. Earthquake ground motions shake buildings in the vertical as well as the horizontal direction, but typically cause the most damage due to building response in the horizontal direction.

The seismic isolators de-couple response by essentially making the fundamental-mode period mode of the isolated structure several time longer than the period of the structure above the isolation system – that is, several times longer than the period of the same structure on a fixed base. In this manner, displacement of the isolation system is "traded" for the force in the structure above the isolation system.



This figure shows 5%-damped and 20%-damped acceleration-displacement response spectra (ADRS) typical of a high seismic region. The ADRS is a plot of response spectral acceleration on the vertical axis and response spectral displacement on the horizontal axis. Spokes from the origin show lines of constant period ranging from 0.5 seconds to 6 seconds. (Click). For shorter, stiffer conventional (fixed-base) structures with fundamental-mode elastic periods of less than about 1.0 second, 5%-damped spectral acceleration ranges from about 0.9g to 1.8g. (Click). By adding seismic isolators, the fundamental-mode period is typically increased to about 2 to 4 seconds and damping is increased to at least 10%, reducing spectral response to about 0.2 to 0.4 g – corresponding to about a factor of 4 reduction in peak lateral force. However, to provide this reduction in lateral force, the seismic isolators must be able to accommodate about 15 to 30 inches of peak lateral displacement. Even larger displacement capacity would be required for isolation systems with longer fundamental-mode periods.

Example – Map of ASCE 7-10 Ground Motions
1-Second MCE_R Spectral Acceleration (Site Class D)



FEMA Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 7

Ground motion intensity varies greatly across the United States as shown by this map of 1-second maximum considered earthquake (MCE_R) spectral acceleration for assumed Site Class D site/soil conditions. Typically, seismic isolation has been used in regions of high seismicity such as the coastal areas of California, Wasatch fault zone (e.g., Salt Lake City, Utah), the New Madrid seismic zone (e.g., Memphis, Tennessee) and the Charleston, South Carolina, seismic zone. Regions of high seismicity provide the greatest opportunity for realizing the benefits of isolation, but also the greatest challenges to the design of the isolation system to accommodate large earthquake displacements.

Background and Basic Concepts
Video of Earthquake Shaking

FEMA   Instructional Material Complementing FEMA P-751, Design Examples   Seismic Isolation - 8

This slide begins with a photo of a commercial building severely damaged by the 1995 M6.8 Kobe earthquake. The building which housed television equipment and related media operations for Nippon Hoso Kyokai (NHK) prior to the earthquake was subsequently demolished. A Japanese video will show a sequence of three clips (Click).

The first clip is from a surveillance video camera inside the NHK during the Kobe earthquake. The next two clips are from shake-table tests of simulated Kobe earthquake response of a typical office and contents – first clip shows office contents response of conventional, fixed-base building, the second clip shows office contents response of an isolated building.

Background and Basic Concepts
Seismic-Code Performance Objectives
(Section 1.1, 2009 *NEHRP Provisions*)

- Intent of these Provisions is to provide reasonable assurance of seismic performance:
  - Avoid serious injury and life loss
  - Avoid loss of function in critical facilities
  - Minimize nonstructural repair costs (where practical to do so)
- Objectives addressed by:
  - Avoiding structural collapse in very rare, extreme ground shaking
  - Limiting damage to structural and nonstructural systems that could lead to injury, economic loss or loss of functions for smaller more frequent ground motions

FEMA Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 9

Section 1.1 of the *Provisions* describes seismic-code performance objectives applicable in concept to all building types, although intended primarily for conventional, fixed-base, buildings. Life-safety (avoiding serious injury and life loss) is explicitly addressed by design for MCE_R ground motions that are intended to avoid collapse in vey rare, extreme ground shaking (i.e., less than 10 percent probability of collapse for MCE_R ground motions). It should be noted that the NHK building met these criteria in the 1995 Kobe earthquake (i.e., the building although severely damage did not collapse). Functional and economic performance objectives are not explicitly addressed by seismic-code design requirements. Rather, it is hoped that additional design strength (i.e., I_e = 1.5) will adequate protect the structure from damage that could close a critical facility (i.e., hospital) and that somehow, nonstructural systems (and contents) can survive the shaking without loss of function or significant economic loss. Note. It is difficult, if not impossible, to design nonstructural systems (and anchor contents) of a conventional fixed-base building such that significant economic and functional losses would not occur for the violent shaking shown in the video of NHK building response during the 1995 Kobe earthquake.

Background and Basic Concepts

Seismic-Code Performance Objectives

(Table C17.2-1 , 2009 *NEHRP Provisions*)

Performance Measure		Earthquake Ground Motion Intensity Level		
Type	Description	Minor	Moderate	Major
Life Safety	Loss of life or serious injury is not expected	**F, I**	**F, I**	**F, I**
Structural Damage	Significant structural damage is not expected	**F, I**	**F, I**	**I**
Nonstructural Damage	Significant nonstructural or contents damage is not expected	**F, I**	**I**	**I**

F indicates fixed-base structures; **I** indicates isolated structures

Instructional Material Complementing FEMA P-751, Design Examples

Seismic Isolation - 10

Seismically isolated structures are expected to perform much better than conventional, fixed-base, structures during moderate and major earthquake ground motions as shown in commentary Table C17.2-1 of the *Provisions* which compares expected performance for fixed-base structures (designated with an “F”) and isolated structures (designated with an “I”)

Background and Basic Concepts
Seismic-Code Performance Objectives
(Implicit for seismically isolated structures)

- Intent of these Provisions is to provide reasonable assurance of seismic performance:
  - Avoid serious injury and life loss
  - Avoid loss of function in ~~critical~~ all facilities
  - Minimize structural, nonstructural and contents repair costs
- Objectives addressed by:
  - Avoiding structural collapse in very rare, extreme ground shaking
  - Avoiding ~~Limiting~~ damage to structural and nonstructural systems and contents that could lead to injury, economic loss or loss of functions for smaller more frequent ground motions by reducing earthquake demands on these systems

FEMA Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 11

Hypothetically, if Section 1.1 of the *Provisions* was revised to specifically address seismically isolated structure performance, then it might read as shown in this slide. The life-safety performance would be the same for fixed-base and isolated structures – that is, avoid structural collapse for very rare, extreme (MCE_R) ground motions. However, avoiding loss of function would not be limited to critical facilities, but apply to all isolated structures, since the same conservative criteria are required for design of the structure above the isolation system regardless of Risk Category (i.e., $R_I \leq 2.0$ and $I_e = 1.0$). Similarly, by reducing earthquake shaking, isolation would provide a practical basis for avoiding damage to all structural and nonstructural systems and contents above the isolation interface.

Background and Basic Concepts
Seismic Isolation Applications – New Buildings

- Motivating Factors
  - Maintain functionality
  - Protect contents
  - Avoid economic loss
- Typical Applications
  - Hospitals
  - Emergency operations centers
  - Other critical facilities (Risk Category IV)
  - Research facilities (laboratories)
  - Hi-tech manufacturing facilities
  - Art museums

FEMA Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 12

The *Standard* applies to new construction. Use of isolation for seismic retrofit has additional motivating factors including protection of historical architecture, minimizing construction cost and impact on facility operation. Typical applications of isolation to new structures include primarily essential (Risk Category IV) facilities and other facilities whose operation immediately after an earthquake is considered to be of particular importance to the owner (hi-tech manufacturing), or which house valuable contents susceptible to earthquake damage (art museums).

An example application of isolation to protect contents (as well as function) is the “new” de Young Museum in the Golden Gate Park of San Francisco, California. The new de Young Museum replaced an existing structure that was programmatically inadequate and seismically deficient, having suffered significant structural damage during the 1989 Loma Prieta earthquake. The museum is located less than 8 km from the San Andreas Fault, and the need to protect the eclectic collections from earthquake damage prompted the owner to opt for base isolation of the low-rise building housing the galleries.

The museum building is seismically isolated with a combination of 76 high-damping elastomeric (rubber) bearings, 76 flat sliding bearings (sliders) and 24 fluid viscous dampers. Bearings and dampers are located in the crawl space below the first floor and interior courtyards, and do not affect museum architecture or function. Unless informed, visitors to the museum are not aware that the building is base isolated. The isolation system selected for the new de Young museum was one of 20 different systems considered for the museum and found by engineering evaluation to be the alternative that had the lowest base shear (best system for superstructure design), the lowest floor acceleration (best system for collection protection) and the lowest cost of the alternatives considered.

Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Delicate Glass Sculpture - *Nijima and Ikehana* Boats
"Chihuly at the de Young" (2008)

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With isolation, the curators of the new de Young Museum can brace or anchor artifacts in a conventional manner and have more freedom with temporary exhibitions. In most cases, bracing can be avoided which would be problematic for many exhibits such as the glass sculpture shown in this photo. Base isolation also made design of the highly irregular superstructure easier, complying with the owner's directive to have as many open spaces as possible.

Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Grade beams and crane Installation

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This photo taken during construction of the new de Young Museum shows grade beams and foundations at individual isolator locations

Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

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This photo taken during construction of the new de Young Museum shows isolators (e.g., sliding bearing at an interior location and a rubber bearing at a perimeter location) and 1st-floor steel framing

Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Steel erection – upper floors

This photo taken during construction of the new de Young Museum shows steel concentric-braces and upper-floor framing

Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Crawl space - rubber bearings on pedestals

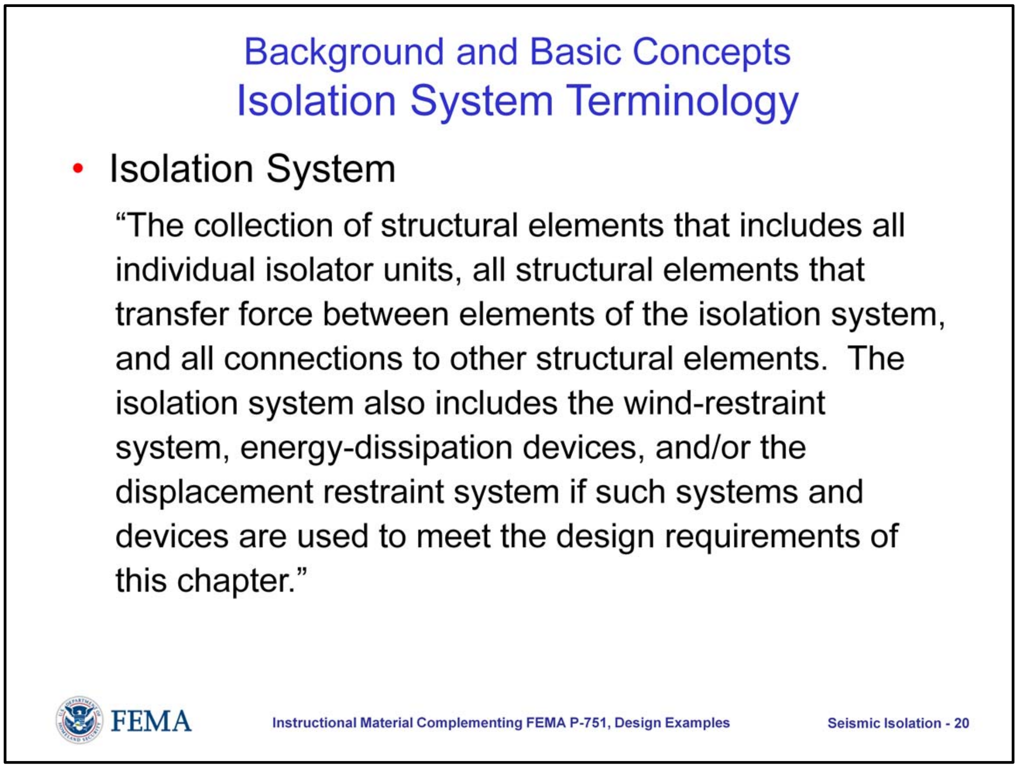
This photo taken in crawl space of the new de Young Museum before addition of fireproofing shows rubber bearings on reinforced-concrete pedestals. A total of 76 high-damping rubber bearings provide restoring force and tend to be located near the perimeter of the building to resist torsion (i.e., rotation of the building during an earthquake).

Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Crawl space – sliding bearing and supplementary fluid viscous damper

This photo taken in crawl space of the new de Young Museum after addition of fireproofing shows a typical stub column on top of a sliding bearing and a fluid viscous damper connected at one end to a 1st-floor girder above and at the other end to a reinforced-concrete pedestal and foundation below. A total of 76 flat sliders provide support, add damping (due to friction) without adding stiffness to the isolation system.

Due to the relatively close proximity to the fault and the potential for large ground motion "pulses," the isolation system incorporates a total of 24 fluid viscous dampers, providing additional displacement control. The covered "moat" around the perimeter of the building accommodates 36 inches of isolated structure displacement in any direction. This clearance includes substantial cushion on the calculated maximum earthquake displacement of 26 inches.



The next three slides describe *Standard* terminology for the isolation system and elements thereof.

The **isolation system** includes the individual isolator units and other structural elements (e.g., connections) that transfer force from the isolator units to the structure and foundation below and to structure above the isolation system. The isolation system also includes energy-dissipation devices (e.g., viscous dampers), wind-restraint system and displacement restraint system, if such systems and devices are used to meet *Standard* requirements. In most applications, wind restraint is an inherent feature of the isolator unit – that is, the initial stiffness of rubber bearings (or the static friction level of sliding bearings) is typically large enough to resist wind design loads without significant displacement. Although uncommon, a displacement restraint system (e.g., moat bumpers, etc.) could be used to limit maximum considered earthquake displacement of the isolation system, provided it is shown that such restraint would not adversely affect the stability of structure above the isolation system.

Background and Basic Concepts
Isolation System Terminology

- Isolator Units

  "A horizontally flexible and vertically stiff element of the isolation system that permits large lateral deformations under design seismic load. An isolator unit is permitted to be used either as part of, or in addition to, the weight-supporting system of the structure."

- Isolation Interface

  "The boundary between the upper portion of the structure, which is isolated, and the lower portion of the structure, which moves rigidly with the ground."

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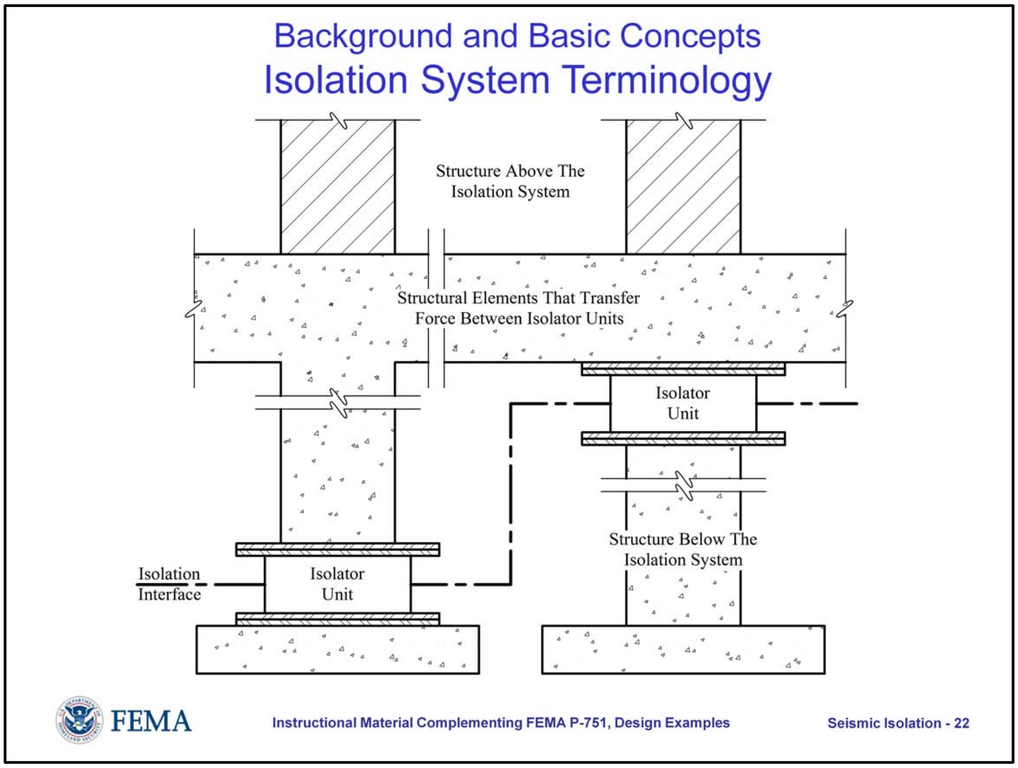
The *Standard* defines **isolator units** as horizontally flexible and vertically stiff elements, assuming that isolation system provides only horizontal isolation. While earthquake damage to buildings and their contents is due primarily to horizontal ground motions, vertical ground motions can adversely affect certain vibration-sensitive equipment and systems. Protection against damage due to vertical (as well as horizontal) ground motions would require a 3-dimensional isolation system, which is not practical for most applications (exceptions include special military facilities and possibly nuclear power plants).

The *Standard* defines the **isolation interface** as an imaginary boundary between the upper portion of the structure which is isolated and the lower portion of the structure which moves rigidly with the ground.



This figure illustrates the isolation interface, the imaginary boundary between the isolated and non-isolated portions of the structure. The isolation interface is often referred to as the “plane of isolation,” although the isolation interface need not be located at single horizontal plane. This figure also illustrates the boundaries between (1) structure above the isolation system, (2) the isolation system, and (3) the structure below the isolation system. Typically, there is a heavy girder or slab just above isolator units to resist large P-Delta moments that occur at peak earthquake displacements of isolator units supporting vertical loads. In this capacity, the heavy girder or slab is considered an element of the isolation system, since it is required for stability of isolators.

Background and Basic Concepts

Isolation Products Used in the United States

- Elastomeric (rubber) Isolators
  - High-damping rubber (HDR) bearings
  - Lead-rubber (LR) bearings
- Sliding Isolators
  - Friction pendulum system (FPS)
    - Single-concave sliding surface bearings
    - Double-concave sliding surface bearings
    - Triple-pendulum bearings
  - Flat sliding bearings (used with rubber isolators)
- Supplementary Dampers
  - Fluid-viscous dampers

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The first seismic isolation systems in buildings in the United States were composed of either high-damping rubber (HDR) or lead-rubber (LR) elastomeric bearings (low-damping rubber bearing with a lead core that adds damping). Other types of isolation systems in the United States include sliding systems ,such as the friction pendulum system, or some combination of elastomeric and sliding isolators. The FPS may be composed of single-concave sliding surface bearings (original “dish” concept), double-concave sliding surface bearings (each with two dishes, one facing up and one facing down), or triple-pendulum bearings (a more sophisticated version of the double-concave bearings). In each case, gravity is used as the restoring force of the FPS. Some applications at sites of very high seismicity (such as that of the de Young Museum in San Francisco) use supplementary fluid-viscous dampers in parallel with either sliding or elastomeric bearings.

Background and Basic Concepts
Acceptable Isolation Systems

- The *Standard* permits the use of any type of isolation system or product provided that the system/isolators:
  - Remain stable for maximum earthquake displacements
  - Provide increasing resistance with increasing displacement
  - Have limited degradation under repeated cycles of earthquake load
  - Have well-established and repeatable engineering properties (effective stiffness and damping)
- The *Standard* does not preclude, but does not fully address 3-D isolation systems that isolate the structure in the vertical, as well as the horizontal direction

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The *Standard* permits a broad range of isolator products that meet certain basic requirements for stability, strength, degradation and reliability. The *Standard* recognizes that the engineering properties of an isolation system, such as effective stiffness and damping, can change during repeated cycles of earthquake response (or otherwise have a range of values). Such changes or variability of design parameters are acceptable provided that the design is based on analyses that conservatively bound the range of possible values of design parameters.

Isolation systems typically provide only horizontal isolation and are rigid or semi-rigid in the vertical direction. While the basic concepts of the *Standard* can be extended to full (3-dieminsional) isolation systems, the requirements are only intended for design of horizontal isolation systems. The design of a full isolation system would require special analyses that explicitly include vertical ground motions and the potential for rocking response of the structure above the isolation interface.

Background and Basic Concepts
General Design Requirements – Isolation System

- The *Standard* (Section 17.2.4) prescribes general design requirements for the isolation system regarding:
  - Environmental Conditions
  - Wind Forces
  - Fire Resistance
  - Lateral Restoring Force
  - Displacement Restraint
  - Vertical-load Stability
  - Overturning
  - Inspection and Replacement
  - Quality Control

FEMA   Instructional Material Complementing FEMA P-751, Design Examples   Seismic Isolation - 25

The *Standard* prescribes general design requirements for design of the isolation system, including environmental conditions (e.g., aging effects, creep, fatigue, operating temperature and exposure to harmful substances)
The isolation system is required to have a wind-restraint system, unless shown (by testing of isolator units) to not displace more than the amount permitted for fixed-base structure for design wind loads.
The isolation system is required to have the same fire resistance as that of comparable structural elements of a fixed-base structure (i.e., columns in the basement of a fixed-base building).
The isolation system is required to have a minimum amount of restoring force at large displacements (i.e., positive post-yield slope) to ensure that isolation system does not accumulate residual displacement in a given direction during repeated cycles of earthquake response.
The isolation system is required to not restrain displacement up to the maximum considered earthquake displacement unless the isolated structure is explicitly designed for the effects thereof.
At maximum considered earthquake displacement, isolators must be stable for “worst-case” vertical loads and the isolated structure must be safe against global overturning (although individual isolators are permitted to uplift during earthquake response, if such does not affect their stability).
Access must be provided for inspection and replacement of isolators,

including pre-occupancy inspection of structural separation areas (moat clearance) and components that cross the isolation interface.

A quality control testing program is required for isolator units (i.e., in addition to testing of isolator unit prototypes).

Background and Basic Concepts
General Design Requirements – Structural System and Nonstructural Components

- The *Standard* (Section 17.2.5) prescribes general design requirements for the structural system regarding:
  - Horizontal Distribution of Force
  - Building Separations
  - Nonbuilding Structures
- The *Standard* (Section 17.2.6) prescribes general design requirements for nonstructural components regarding:
  - Components at or above the Isolation Interface
  - Components Crossing the Isolation Interface
  - Components below the Isolation Interface

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The *Standard* prescribes general design requirements for design of the structural system and for nonstructural components.
The isolated structure be must separated from surrounding retaining walls, etc. (moat clearance) by at least the maximum considered earthquake displacement
Isolated non-building structures (e.g., seismically isolated tank, etc.) must be designed and constructed in accordance with Chapter 15 of the *Standard* using displacements and forces of Sections 17.5 or 17.6.
Nonstructural components above the isolation interface (isolated components) must be anchored/braced for force corresponding to maximum dynamic response of the isolated structure, or by exception may be anchored/braced for fixed-base building design requirements (which would be conservative, but would also avoid calculation of peak dynamic response of the isolated structure)
Nonstructural components that cross isolation interface (e.g., water and fire piping, electrical conduit, HVAC ductwork, etc.) must be designed to accommodate maximum earthquake displacement
Nonstructural components below the isolation interface must be anchored/braced for fixed-base building design requirements.

Criteria Selection
Acceptable Methods of Analysis*

Site Conditions or Structure Configuration Criteria	ELF Procedure	Response Spectrum	Time History
Site Conditions			
Near-Source ($S_1 \geq 0.6$)	NP	P	P
Soft soil (Site Class E or F)	NP	NP	P
Superstructure Configuration			
Flexible or irregular superstructure (h > 4 stories, h > 65 ft., or $T_M > 3.0$ s, or $T_D \leq 3T$)**	NP	P	P
Nonlinear superstructure (requiring explicit modeling of nonlinear elements, Sec. 17.6.2.2.1)	NP	NP	P
Isolation System Configuration			
Highly nonlinear isolation system or does not	NP	NP	P

* P indicates permitted and NP indicates not permitted by the *Standard*
** T is the elastic, fixed-base, period of the structure above the isolation system

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Seismic Isolation - 27

The equivalent lateral force (ELF) procedure is intended primarily to prescribe minimum design criteria and may be used for design of a very limited class of isolated structures (without confirmatory dynamic analyses). The simple equations of the ELF procedure are useful tools for preliminary design and provide a means of expeditious review and checking of more complex calculations. Modal (Response Spectrum) analysis is permitted if the site is relative stiff (not Site Class E of F) and the superstructure is essentially elastic (does not require explicit modeling of nonlinear elements) and the isolation system is not “highly nonlinear.” The last criterion is often assumed to not be met (even when it is) and most isolated building designs are validated using seismic response history (time history) analysis.

Background and Basic Concepts
Design Approach

- Design the structure above the isolation system for forces associated with design earthquake ground motions, reduced by only a fraction of the factor permitted for design of conventional, fixed-base buildings (R_I = 3/8R ≤ 2.0)
- Design the isolation system and the structure below the isolation system (e.g., the foundation) for unreduced design earthquake forces (R_I = 1.0)
- Design and prototype test isolator units for forces (including effects of overturning) and displacements associated with the maximum considered earthquake (MCE_R) ground motions
- Provide sufficient separation between the isolated structure and surrounding retaining walls and other fixed obstructions to allow unrestricted movement during MCE_R ground motions

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The design approach of the *Standard* for isolated structures is to (1) protect the isolated structure from significant earthquake damage for design earthquake ground motions, and (2) to protect the isolation system form failure for maximum considered earthquake ground motions (e.g., collapse performance comparable to that of fixed-base structures).

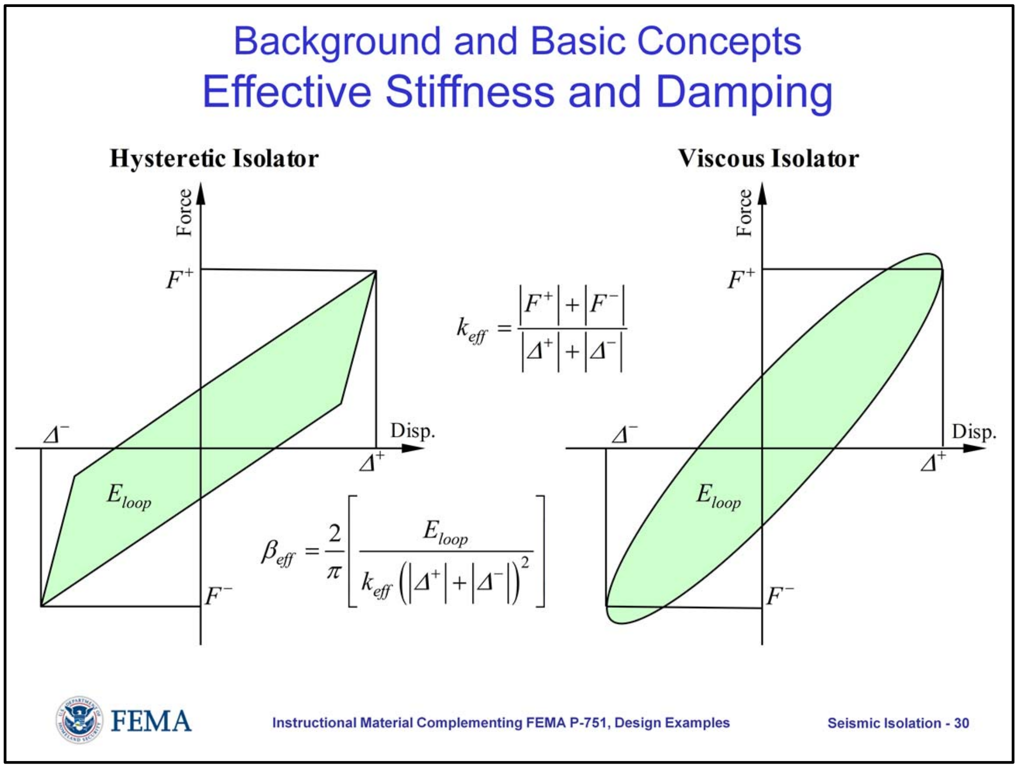
Background and Basic Concepts
Design Approach

- Design the structure above the isolation system, the isolation system, and the structure below the isolation system (e.g., the foundation) for more critical of loads based on bounding values of isolation system force-deflection properties:
  - Design the isolation system for displacements based on minimum effective stiffness of the isolation system
  - Design the structure above for forces based on maximum effective stiffness of the isolation system
- Variations in Material Properties (Section 17.1.1):

"The analysis of seismically isolated structures, including the substructure, isolators, and superstructure, shall consider variations in seismic isolator material properties including changes due to aging, contamination, environmental exposure, loading rate, scragging and temperature."

FEMA Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 29

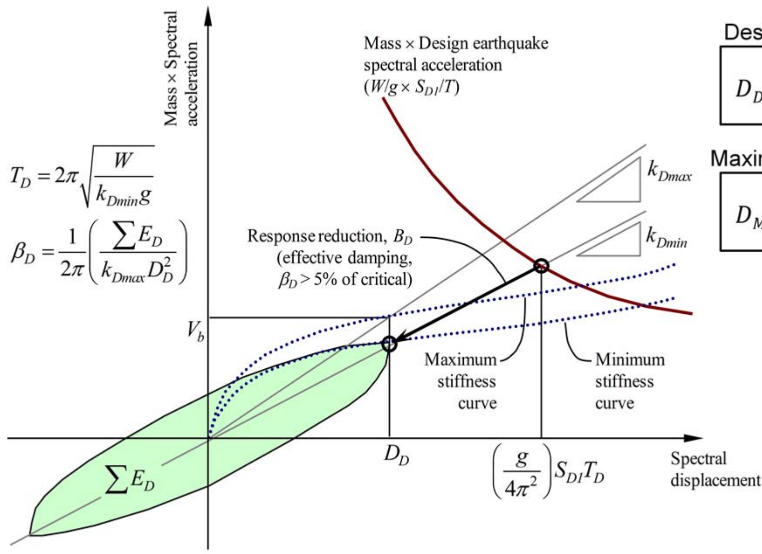
The design approach of the *Standard* for isolated structures is to explicitly incorporate uncertainty in the properties of the isolation system due to (1) variation in effective stiffness and damping properties determined by prototype testing, (2) variation in material properties of isolators due to aging, etc., and (3) other potential sources of uncertainty such as those due to manufacturing (e.g., isolator fabrication tolerances). Explicit incorporation of uncertainty in the design properties of the isolation system is fundamentally different and more conservative than the design approach used for other (fixed-base) structures.



This figure illustrates the calculation of the effective stiffness and the effective damping for an isolator unit with either purely hysteretic or purely viscous damping behavior. In the case of viscous damping, the area of the hysteresis loop (E_{loop}) corresponds to dynamic cyclic response at the period of the isolated structure (i.e., at velocities representing earthquake response). In general (and for all hysteretic systems), effective properties are amplitude-dependent.

This slide concludes the first part of presentation that has addressed background and basic concepts of seismic isolation and Code design requirements. The next part of the presentation will focus on equivalent lateral force (ELF) design methods, modeling and analysis of the isolation system, and dynamic lateral response analysis procedures.

Equivalent Lateral Force Procedure
Isolation System Displacement (D_D and D_M)



Design Displacement

$$D_D = \left(\frac{g}{4\pi^2}\right)\frac{S_{D1}T_D}{B_D}$$

Maximum Displacement

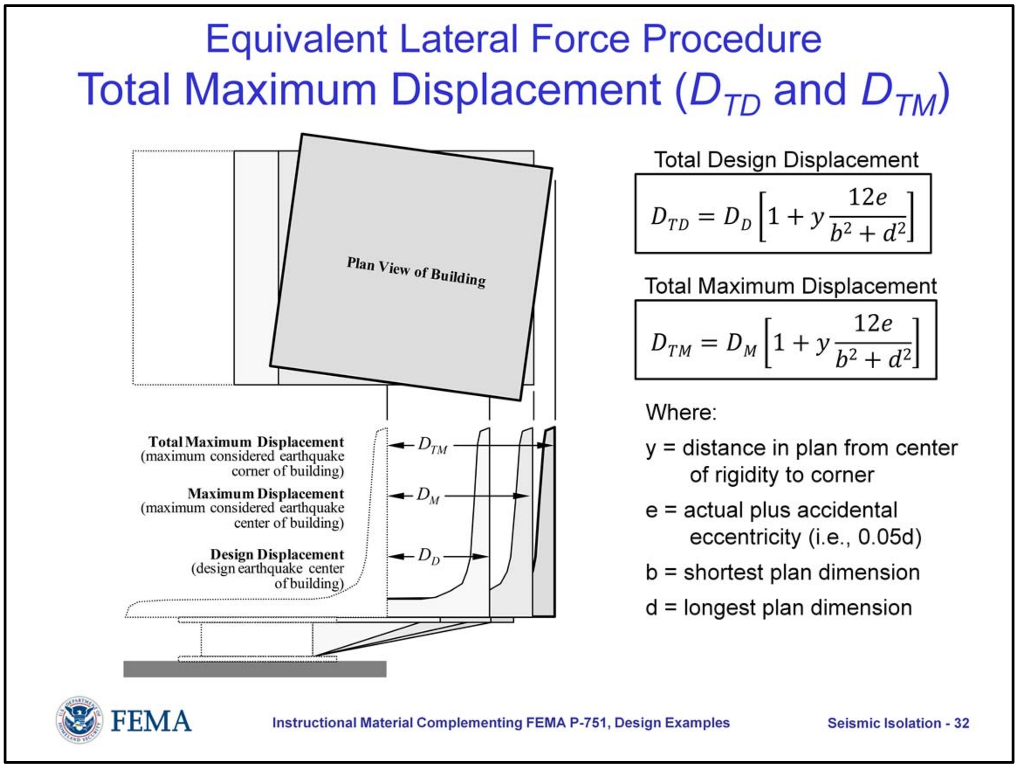
$$D_M = \left(\frac{g}{4\pi^2}\right)\frac{S_{M1}T_M}{B_M}$$

B_D, B_M	β_D, β_M
0.8	≤ 2%
1.0	5%
1.2	10%
1.35	15%
1.5	20%
1.7	30%

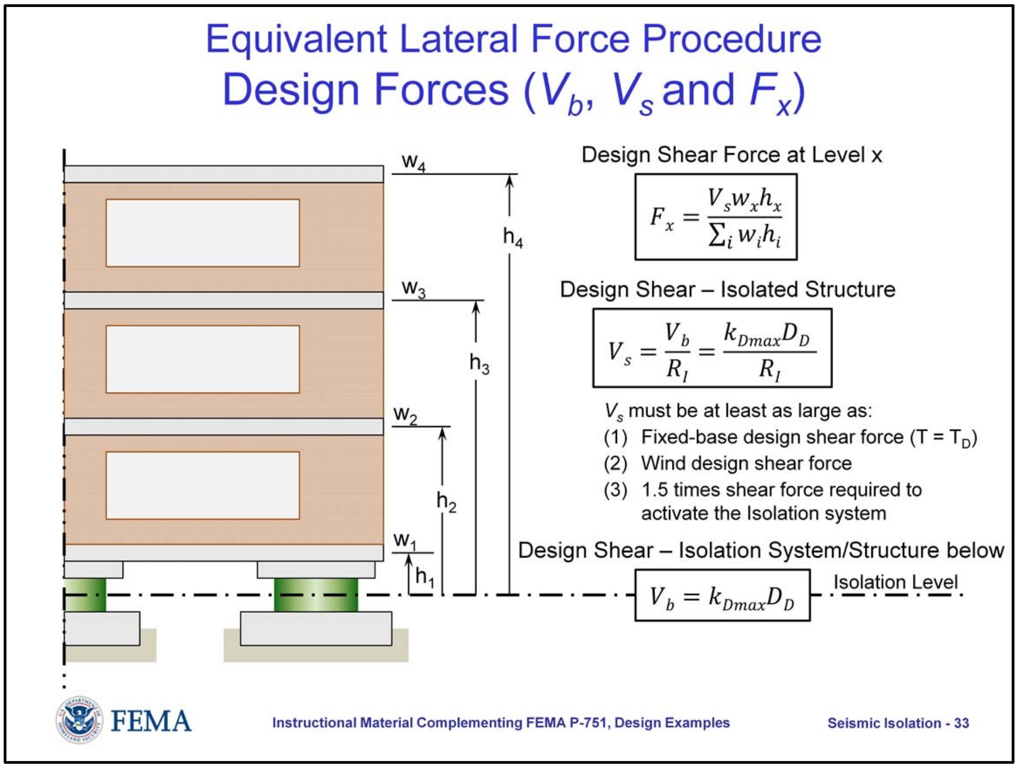
FEMA Instructional Material Complementing FEMA P-751, Design Examples — Seismic Isolation - 31

This figure illustrates definitions and formulas of the amplitude-dependent values of effective period (T_D) and effective damping (β_D) used to calculate the design displacement (D_D). The maximum displacement (D_M) is calculated in the same manner (only for MCE_R ground motions which are 50 percent stronger) using amplitude-dependent values of effective period (T_M) and effective damping (β_M). Due to the inherent nonlinear nature of isolation system stiffness, the effective period at maximum displacement tends to be a somewhat larger than that at the design displacement, and effective damping at maximum displacement tends to be somewhat less than that at the design displacement for the same system.

The value of 1-second MCE_R 5%-damped spectral acceleration (S_{M1}) is given in Section 11.4.3 of the *Standard* and is the product of the site factor (F_v) and the 1-second MCE_R spectral acceleration (S_1) provided by USGS maps of ground motion values. The value of 1-second design 5%-damped spectral acceleration (S_{D1}), defined as 2/3 of S_{M1} in Section 11.4.4 of the Standard, is the same 1-second spectral acceleration as that used for design of conventional fixed-base structures (albeit with a very different response modification factor).



This figure illustrates definitions and formulas for “total” displacement at corners of the isolated structure that includes potential rotation, as well as, translation of the isolation system. Total displacement is calculated as a factor (not less than 1.1) times translation-only displacement. This factor is based on the buildings center of rigidity, plan dimensions and actual plus accidental mass eccentricity. The key assumption underlying these equations is that the distribution of isolator effective stiffness in plan is proportional to the distribution of mass (supported weight) of the structure above. 5% percent eccentricity increases corner displacement by about 15% for buildings square in plan, and by abut 30% for buildings that longest dimensions many times greater than the other. Systems with proportional stiffer isolators near the perimeter of structure (e.g., de Young Museum) provide greater resistance to torsion and the effects of actual plus accidental mass eccentricity. Total maximum displacement (D_{TM}) is used to verify stability of isolators for vertical loads and to establish minimum moat clearance.



The unreduced design base shear force (V_b), the product of the upper-bound value of effective stiffness (k_{Dmax}) and the design displacement (D_D), is required for design of the isolation system, foundations, and other structure below the isolation system. The base shear required for design of the structure above the isolation system (V_s), is reduced by the response modification factor (R_I) which has values ranging between 1.0 and 2.0. Design forces are distributed over the height of the building above the isolation level assuming an inverted-triangular distribution which is, in general, a conservative distribution for isolated structures, particularly for isolated structures with a heavy first floor.

Equivalent Lateral Force Procedure
Response Modification Factor (R_I)

- Response modification factor (R_I) required for design of the structure above the isolation system is limited to:

$$R_I = \frac{3}{8}R \leq 2$$

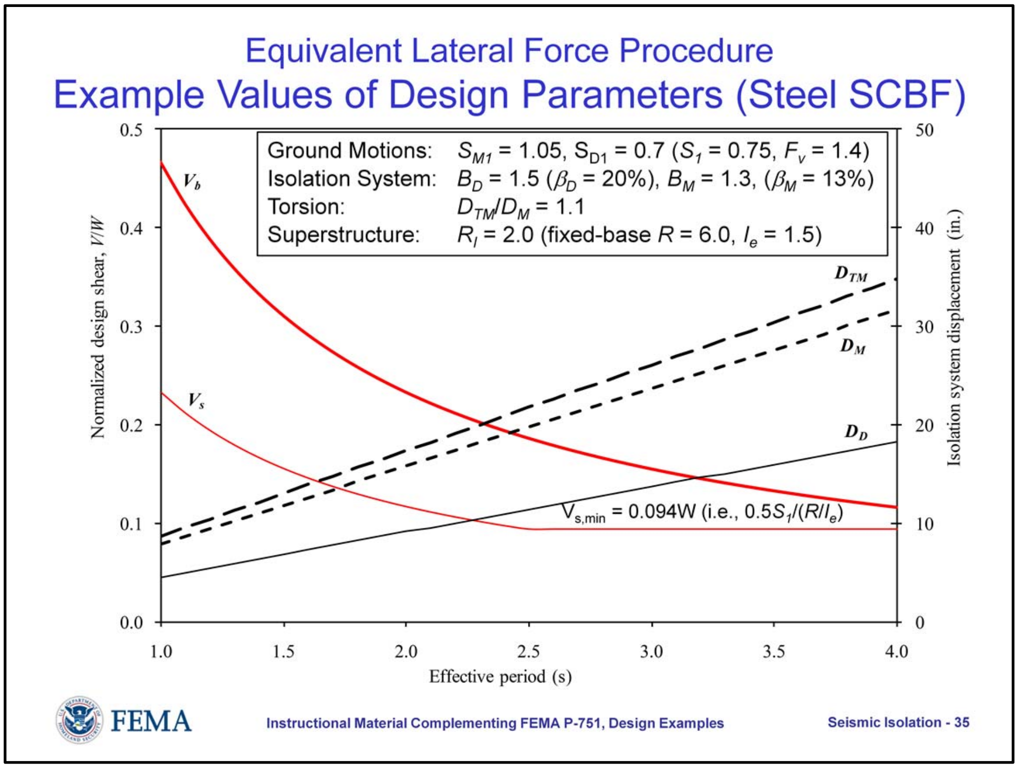
- Example values of R_I for high-seismic SDC D, E and F structures:

Seismic Force Resisting System	*Standard*		*IBC*	
	Fixed Base (R)	Isolated (R_I)	Fixed Base (R)	Isolated (R_I)
Steel Ordinary Concentric Brace Frames	3¼[1]	1.2	3¼[1]	1.0[2]
Steel Special Concentric Braced Frames	6	2	6	2
Steel Ordinary Moment Frames	NP	NP	NP	1.0[2]
Steel Special Moment Frames	8	2	8	2

1. Limited to 35 feet (SDC D and E); NP in SDC F
2. 2006 IBC permits steel OCBFs and steel OMFs designed for R_I = 1.0 and AISC 341

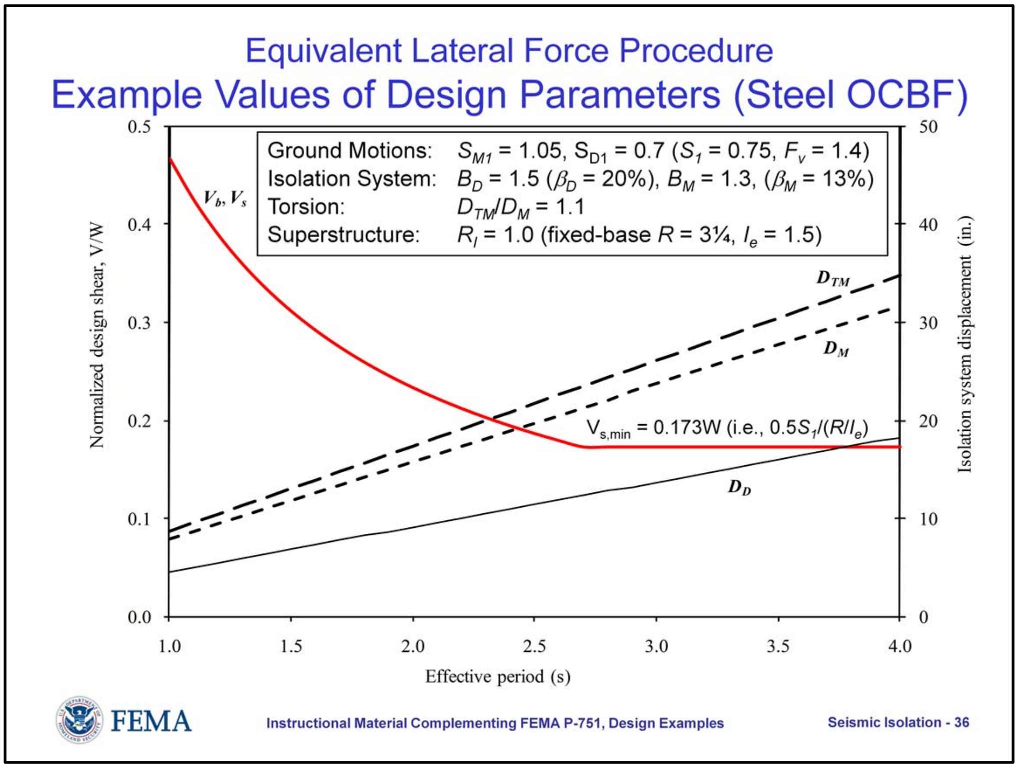
Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 34

The response modification factor (R_I) is defined as 3/8 of the R factor (from Table 12.2-1) of the seismic force resisting system of the structure above the isolation system, but not greater the 2.0. Systems not permitted for use in conventional, fixed-base, buildings (e.g., in high seismic regions) are also not permitted by the *Standard* for isolated structures. The 2006 IBC modified this concept to allow use of OCBFs and OMFs in high-seismic regions (i.e., SDC D, E and F structures) if designed for R_I = 1.0 and AISC 341.



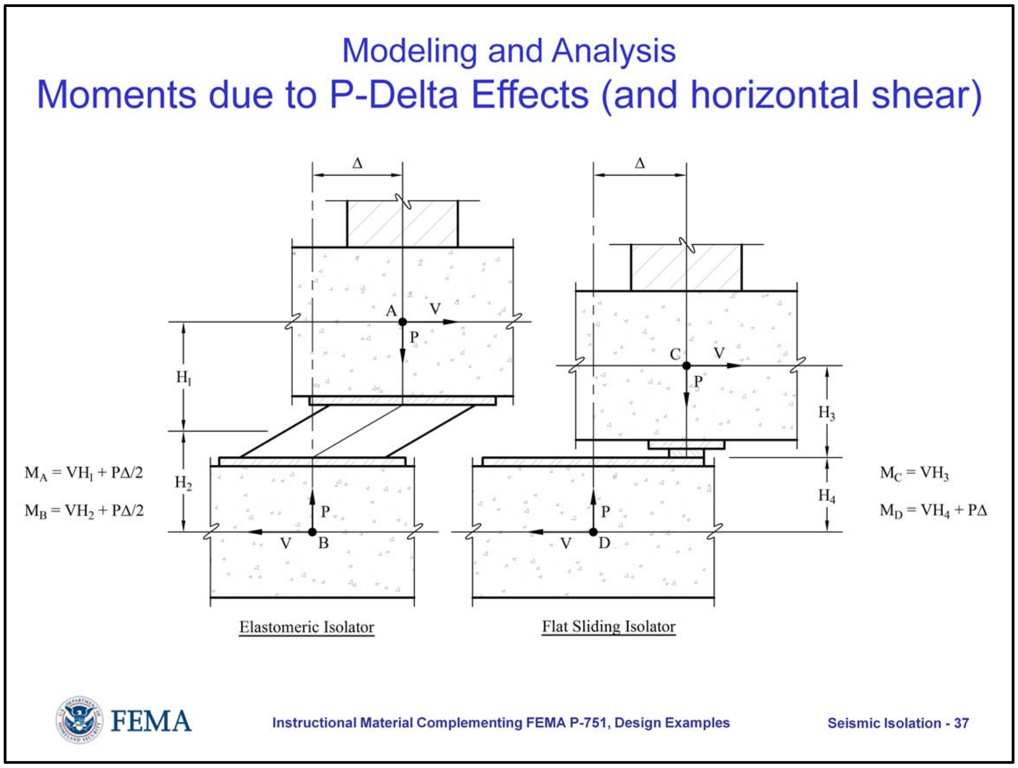
This figure illustrates the trade-off between isolated structure design forces (normalized by building weight) and isolation system displacement as a function of effective period for a steel special concentric braced frame (SCBF) system. Design shear forces decrease (subject to certain limits) and design displacements increase as the isolated period increases. The ground motion design values (i.e., corresponding to a region of high seismicity) and force-deflection properties of the isolation system used to develop the design parameters shown in this figure are the same as those used for the emergency operation center (EOC) design example covered later in this presentation.

Note. The minimum value of design base shear ($V_{s,min}$) is based on the requirement of *Standard* Section 17.5.4.3 that the structure above the isolation system be designed for not less than the base shear required by Section 12.8 for a fixed-base structure of the same effective seismic weight and period (T_D) as that of the isolated structure. As shown above, minimum value of base shear is about 0.10W applies to isolated periods of about 2.5 seconds, and greater.



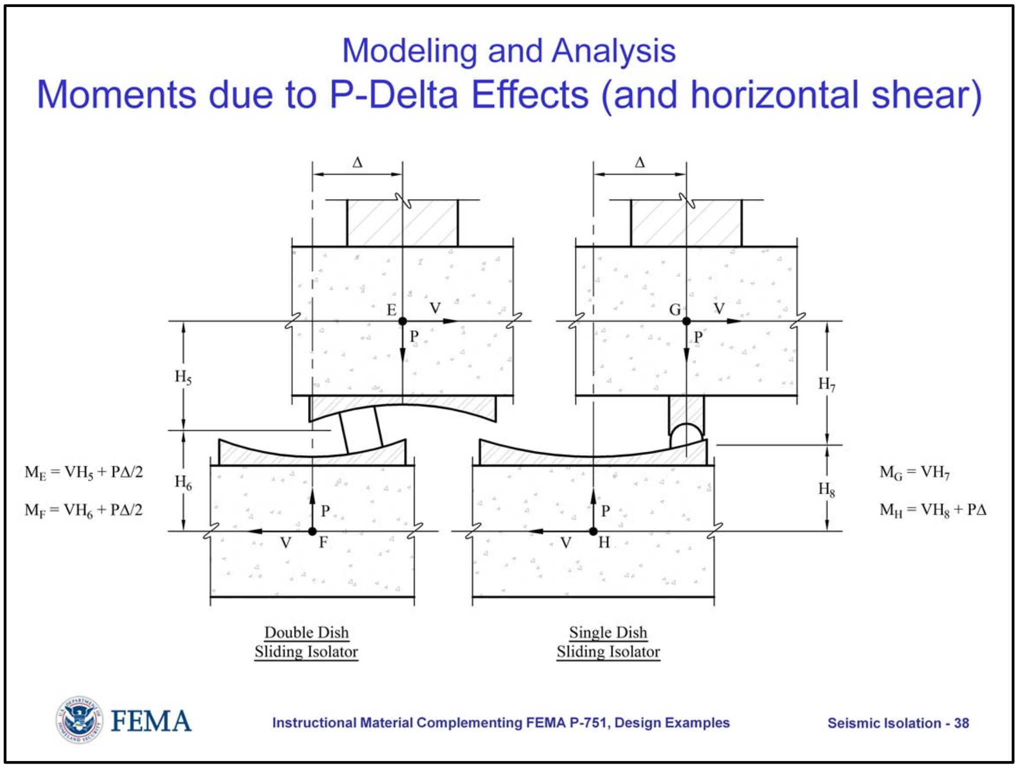
This figure illustrates the trade-off between isolated structure design forces (normalized by building weight) and isolation system displacement as a function of effective period for a steel ordinary concentric braced frame (OCBF) system.

The ground motion design values (i.e., corresponding to a region of high seismicity) and force-deflection properties of the isolation system used to develop the design parameters shown in this figure are the same as those of the previous slide (of design parameters for a steel SCBF system. The only differences are in the values of the *R* factor (i.e., 6 for fixed-base steel SCBFs and 3¼ for steel fixed-base steel OCBFs) and the R_I factor (2 for isolated steel SCBFs and 1.0 for fixed-base steel OCBFs).

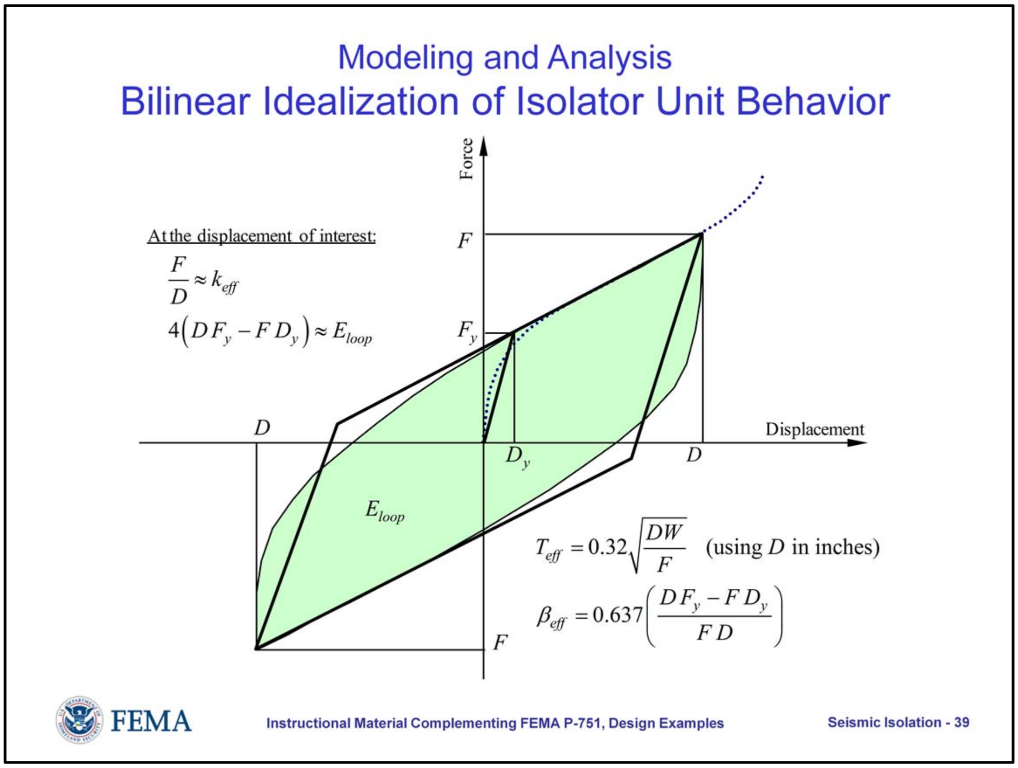


The next two slides illustrate moments in the structure above and structure (foundation) below due to P-Delta effects and horizontal shear for different types of seismic isolators. Moments due to P-Delta effects are typically quite large and require special consideration in the modeling and analysis of isolated structures.

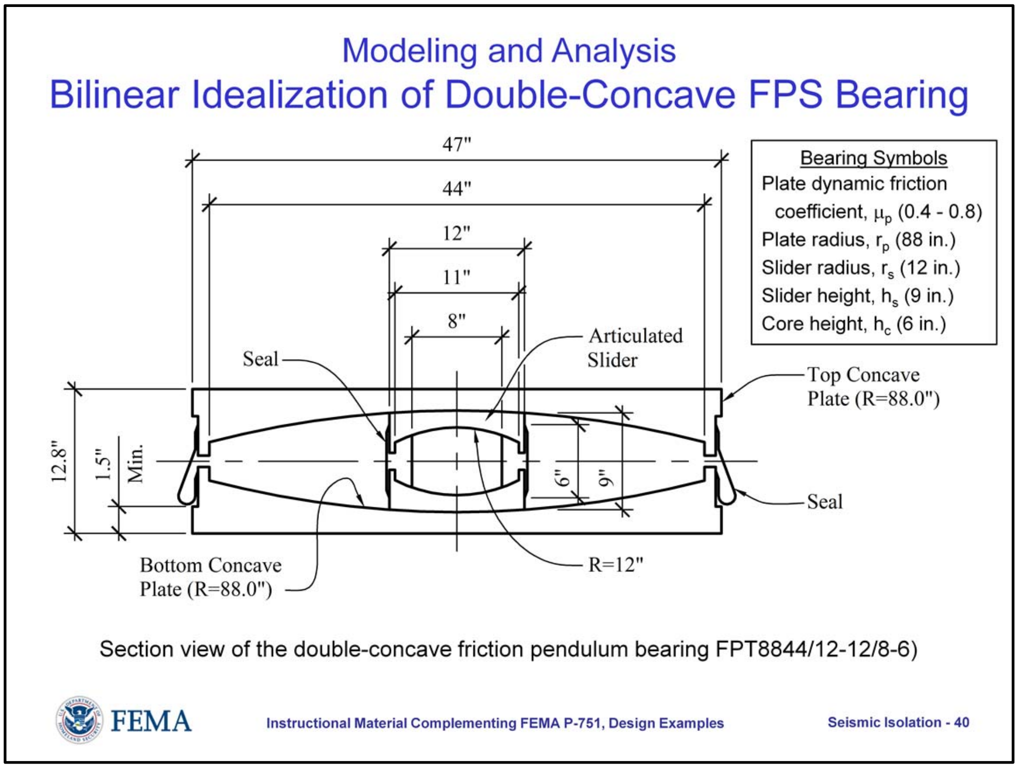
In this slide, moments are shown on the left for a elastomeric isolator (i.e.., either high-damping rubber or lead-rubber bearing) and on the right for a flat sliding isolator with the sliding surface at the base (face up). In the case of the elastomeric isolator P-Delta moment is shared approximately equally between the structure above and foundation below. In the case of the flat slider, the P-Delta moment is resisted entirely by the foundation below. Note. If the sliding surface was at the top (face down), then the P-Delta moment would be resisted entirely by the structure above.



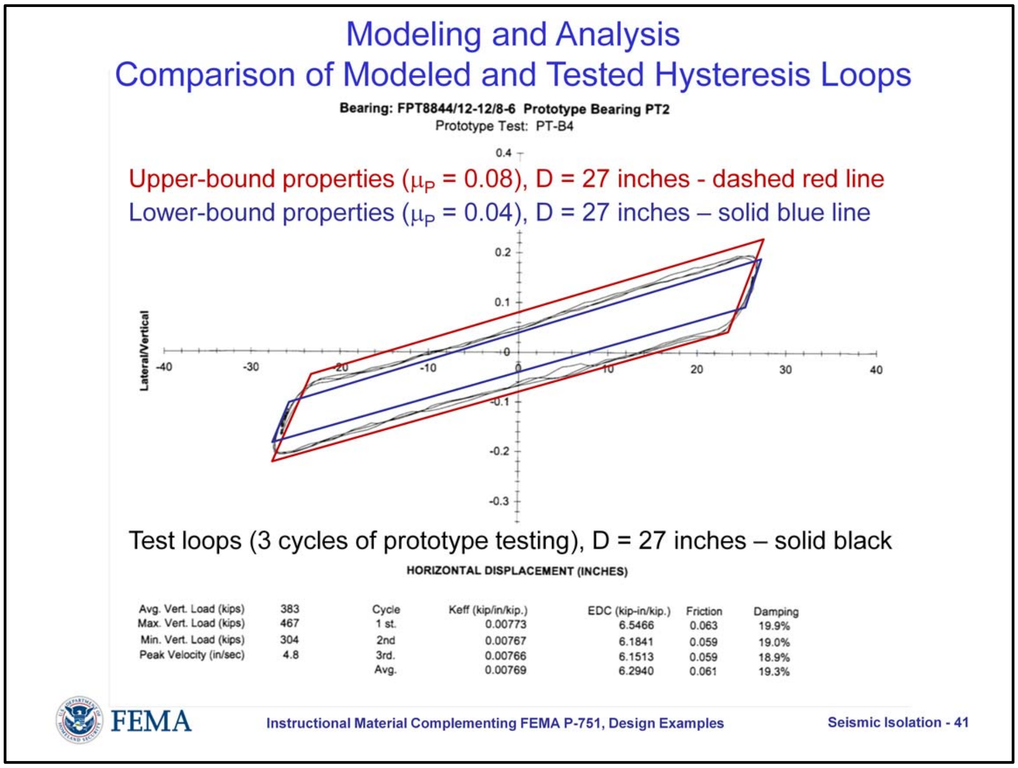
In this slide, moments are shown on the left for a double dish (or double concave) sliding isolator and on the right for a single dish sliding isolator with the sliding surface at the base (face up). In the case of the double dish sliding isolator, P-Delta moment is shared approximately equally between the structure above and foundation below similar to an elastomeric isolator. In the case of the single dish sliding isolator, P-Delta moment is resisted entirely by the foundation below. Note. If the sliding surface was at the top (dish facing down), then the P-Delta moment would be resisted entirely by the structure above.



This figure illustrates the bilinear idealization of an isolator unit and simple formulas for the effective period, T_{eff}, and effective damping, β_{eff}, based on the yield point (D_y, F_y) and the point of peak response (D, Y). Although more sophisticated idealizations could be used, the relatively simple bilinear idealization of isolator behavior provides acceptably accurate estimates of effective period and effective damping for most elastomeric and friction-pendulum (dish) sliding bearings at large displacements (i.e., $D >> D_y$). The bilinear idealization reflects the inherent amplitude-dependent behavior of the effective period which tends to increase with increasing displacement and effective damping which tends to decrease with increasing displacement. The bilinear idealization does not (can not) capture behavior of isolators at extreme displacements which include stiffening of elastomeric bearings at high strains in the rubber (e.g., 300% strain), engagement of the sliding element and the lip of the dish of the friction-pendulum sliding bearing (for dish isolators that have lips), or the complex behavior of the FPS triple-pendulum bearing.

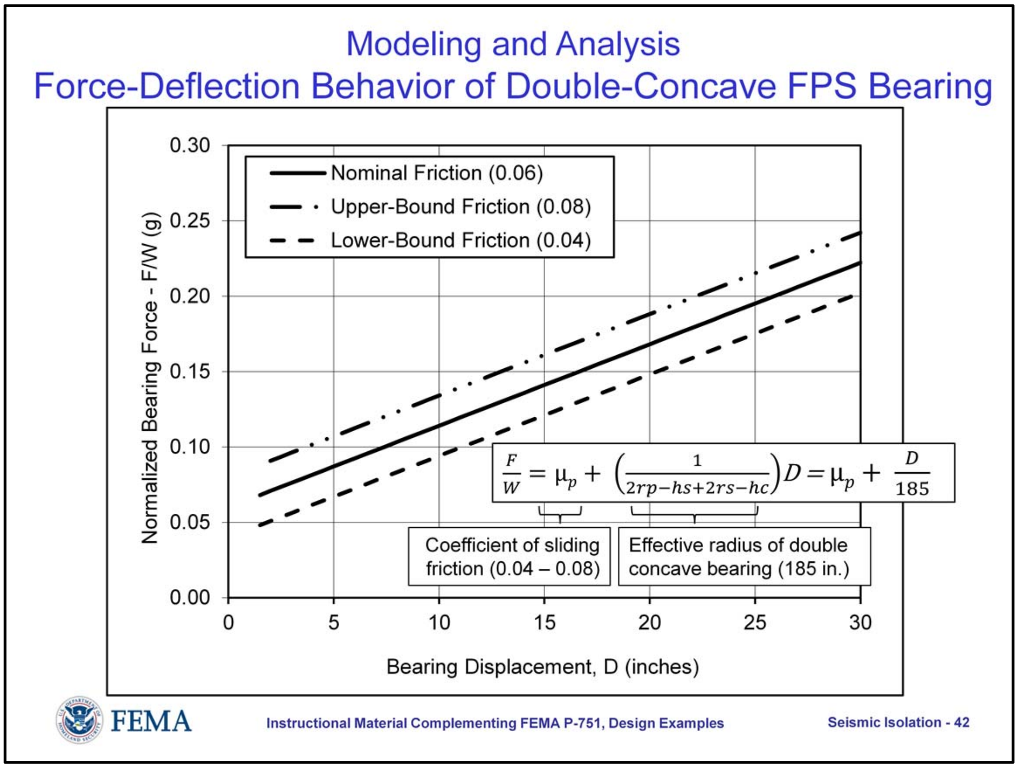


This slide shows a section view and dimensions of a double-concave friction pendulum system (FPS) bearing (FPT8844/12-12/8-6, manufactured by Earthquake Protection Systems). FPS bearings can be fabricated to have different amounts of dynamic friction (i.e., friction at interfaces between the articulated slider element and the top and bottom concave plates). For this isolator, the nominal value of dynamic friction is 0.06 for both top and bottom plate surfaces, and the lower-bound and upper-bound values of dynamic friction are assumed to range from 0.04 to 0.08 considering all possible sources of variability (i.e., aging and environmental effects, manufacturing tolerances and prototype testing) as illustrated by the hysteresis loops shown in the next slide.

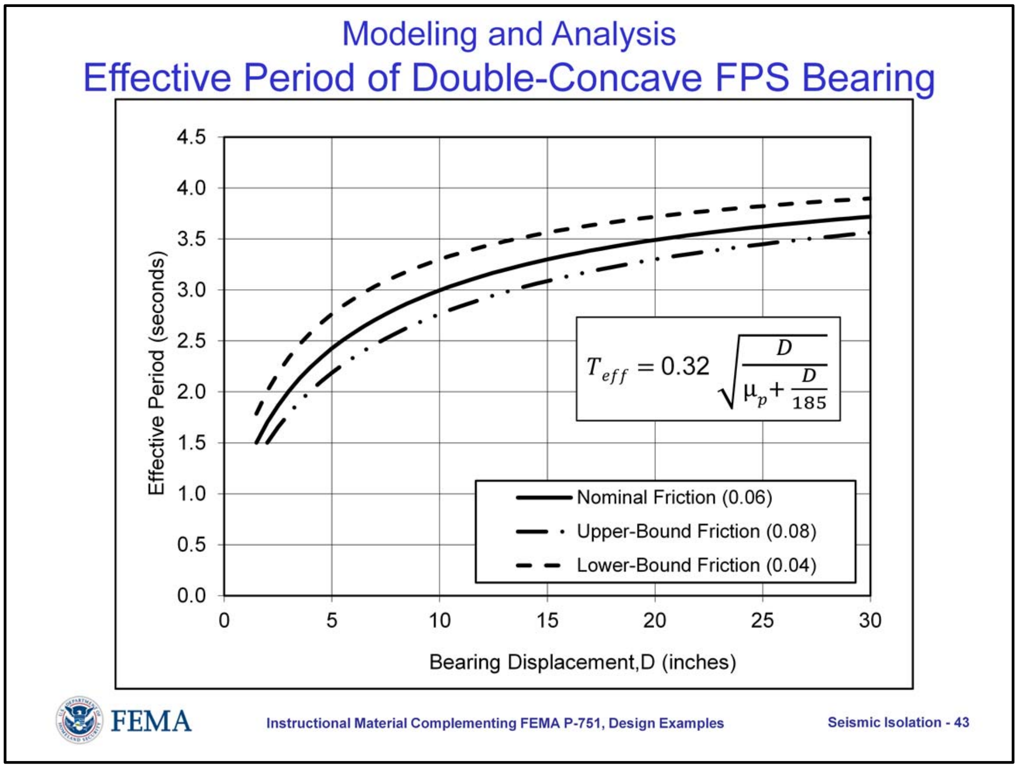


This figure shows modeled and tested hysteresis loops for the double-concave FPS bearing at peak displacements of plus/minus 27 inches. The lower-bound and upper-bound loop properties are based on values of dynamic friction of 0.04 and 0.08, respectively, and are intended to bound variation in properties due to aging and environmental effects, manufacturing tolerances as well test loop variation.

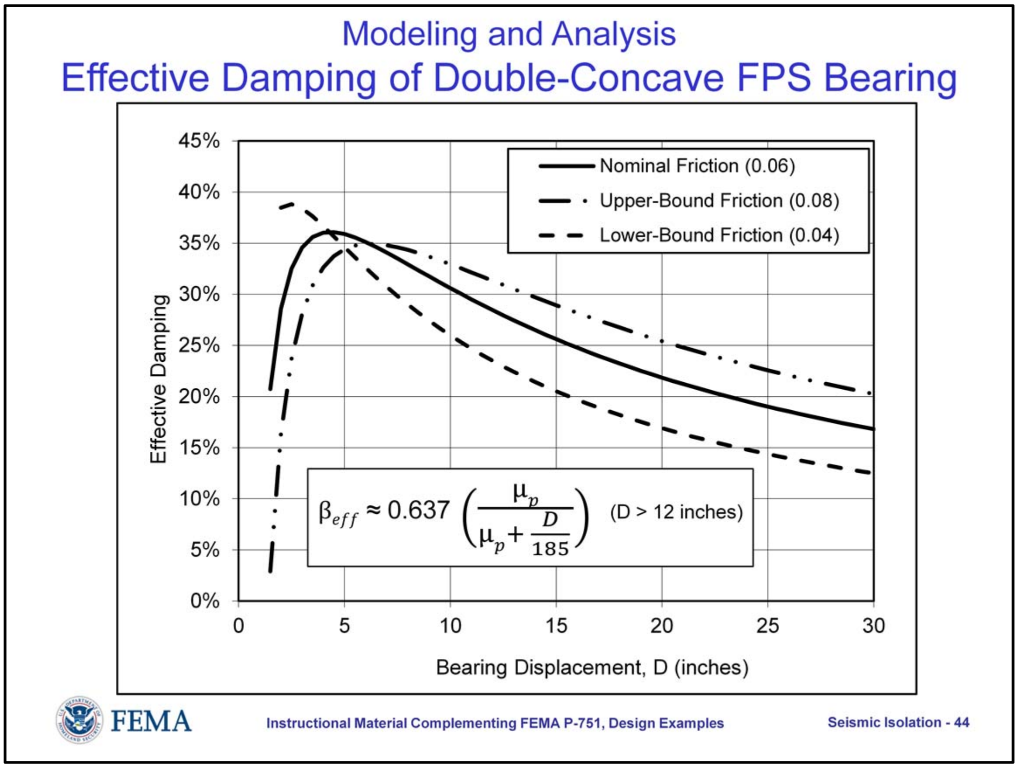
Note. The effective stiffness (used to calculate effective period) and effective damping are amplitude dependent. Therefore, the values of effective period and effective damping used for ELF design are a function of ground motion intensity (i.e., seismic design values for the site of interest), as well as the properties of the bearing. The next three slides illustrate theoretical values of normalized force, effective period and effective damping as a function of bearing displacement of the double-concave FPS bearing. In each slide, values of the parameter of interest are shown for nominal (0.06), upper-bound (0.08) and lower-bound (0.04) values of dynamic friction. These curves are useful aids during preliminary ELF design of the isolation system.



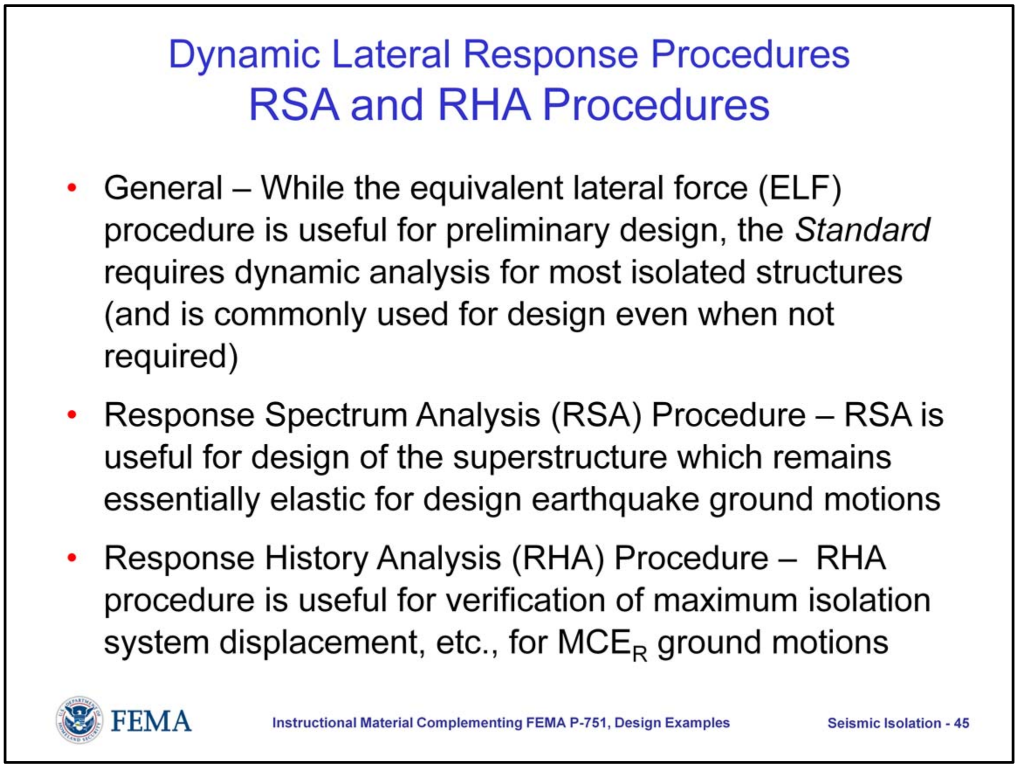
This figure shows normalized bearing force (i.e., lateral restoring force) of the double-concave bearing. Lateral restoring force is a function of the dynamic friction coefficient and effective radius of double-concave configuration (i.e., approximately 185 inches, the sum of the two dish radii less the height sliding elements). Note. When friction is nil, the restoring force is a linear function of displacement divided by the effective radius.



This figure shows the effective period of the double-concave FPS bearing as a function of the dynamic friction coefficient and effective radius of double-concave configuration (185 inches). Note. When friction is nil, the effective period formula is same as that of a pendulum, 185 inches in length. This figure illustrates the increase in the effective period with increasing displacement.



This figure shows the approximate effective damping of the double-concave FPS bearing as a function of the dynamic friction coefficient and effective radius of double-concave configuration (185 inches). The curves shown are intentionally conservative (at small displacements) and the approximate formula only applies to relatively large displacements (D > 12 inch), which are of primary interest. At large displacements, the figure illustrates the decrease in the effective damping with increasing displacement and the importance of the amount of dynamic friction on the value of effective damping.



Standard Section 17.4 requires dynamic analysis for isolated structures that:

1. Are potentially near an active fault ($S_1 \geq 0.6g$)
2. Are on a “soft” soil site (Site Class E or F)
3. Are “tall” (over 4 stories in height)
4. Have a very long isolated period ($T_M > 3.0$ seconds)
5. Have a relatively flexible superstructure ($3T > T_D$)
6. Have an irregular superstructure, or
7. Have an isolation system with excessive damping, inadequate restoring force, or displacement restraint.

These criteria effectively require dynamic analysis for most isolated structures, although ironically dynamic analysis is not required for more dynamically complex fixed-base structures that do not meet these criteria (when applicable)

Dynamic Lateral Response Procedures
Minimum Design Criteria

- The *Standard* encourages the use of dynamic analysis but recognizes that along with the benefits of more complex model methods also comes an increased chance of error – to avoid possible under-design, the Standard establishes lower-bound limits of the results of RSA and RHA as a percentage of the ELF design parameter:

ELF Design Parameter		Percent of ELF	
Description	Symbol	RSA	RHA
Total Design Displacement	D_{TD}	90%	90%
Total Maximum Displacement	D_{TM}	80%	80%
Design Force – Isolation System (and below)	V_b	90%	90%
Design Force - Irregular Superstructure	V_s	100%	80%

Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 46

The *Standard* establishes a “safety-net” of minimum displacement and force requirements based on a percentage of ELF design values. The primary concern is that response history analysis could be misused. The ELF formulas provide an easy means of checking for gross errors.

Dynamic Lateral Response Procedures
Modeling Requirements

- Configuration - Dynamic analysis models should account for:
  - Spatial distribution of individual isolator units
  - Effects of actual (and accidental) mass eccentricity
  - Overturning forces and uplift of individual isolator units
  - Variability of isolation system properties (i.e., upper-bound and lower-bound values of stiffness and damping)
- Nonlinear Properties of the Isolators – Model should incorporate nonlinear properties of isolators determined from testing of prototype units (e.g., consistent with effective stiffness and effective damping properties of the ELF procedure)
- Nonlinear Properties of the Superstructure – Model should incorporate nonlinear properties of the superstructure, if RSA is used to justify loads less than those permitted for ELF (not typical)

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The *Standard* requires dynamic analysis models to accurately represent building geometry and behavior, including the capability of evaluating uplift of individual isolator units. Like ELF methods, dynamic analysis models must evaluate response for upper-bound and lower-bound values of isolation system properties, where bounding values are based on prototype testing of isolator units and incorporate aging and environmental effects and other sources of variability. Typically, the superstructure is modeled with linear elastic elements and only the isolators (and dampers, if used) are modeled as nonlinear elements.

Dynamic Lateral Response Procedures
Response Spectrum Analysis (RSA)

- Amplitude-dependent values of isolator properties:
  - Same effective stiffness and effective damping properties of isolators as those of the ELF procedure (including separate models/analyses of maximum and minimum values of effective stiffness)
- Modal Damping
  - Effective damping of isolated modes limited to 30 percent of critical
  - Higher modes typically assumed to have 2 to 5 percent damping
- 100%-30% Combination of Horizontal Earthquake Effects
  - Q_E = Max $(1.0Q_{EX} + 0.3Q_{EY}, 0.3Q_{EX} + 1.0Q_{EY})$
- Story Design Shear Force Limit
  - Design story shear forces are limited to those of the ELF distribution (over height) anchored to the RSA value of design base shear, V_s

FEMA Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 48

Response spectrum analysis (RSA) requires equivalent linear properties of the isolation system which (like ELF methods) are amplitude dependent. Thus, at least four models are required for RSA which are the combinations of upper-bound and lower-bound properties of the isolation system at design earthquake intensity and upper-bound and lower-bound properties at MCE_R intensity.

The *Standard* requires 100%-30% of horizontal responses for RSA which is conservative for peak response of isolated modes using maximum direction ground motions. The RSA story design shear force limit is required to avoid underestimation of higher-mode response when isolators are modeled with effective rather than actual properties. The RSA story design shear force limit is based on the values of V_s calculated by RSA. Although not explicitly required by the *Standard*, the value of V_s used for RSA design should not be taken as less than any of ELF limits on base shear (e.g., 1.5 times shear force required to activate the isolation system).

Dynamic Lateral Response Procedures
Response History Analysis (RSA)

- Explicit modeling of nonlinear properties:
  - Typical for modeling of Isolator units
  - Not typical for other elements of the structure
- At least 3 earthquake records:
  - Design based on the maximum response of the 3 records
  - Design based on the average response if 7, or more, records
- Earthquake record selection and scaling:
  - Records are selected with site properties (e.g., soil type), site-to-source distances, and source properties (i.e., fault type, magnitude, etc.) consistent with those that dominate seismic hazard at the site of interest
  - Selected records are scaled to match the “target” spectrum of either design earthquake or MCE_R ground motions over the period range of interest (e.g., $0.5T_M$ to $1.25T_M$).

FEMA Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 49

While RHA is most commonly used for dynamic analysis of isolated structures, it is problematic for design since the number of analyses required to address bounding values of properties, multiple locations of accidental mass eccentricity, etc., produce an overwhelming number of data.

While the *Standard* permits as few as 3 earthquake records, 7 earthquake records are typically used RHA, so that the design may be based on the average value of the response parameter of interest. There is no unique set of earthquake records, and earthquake records are typically developed on a project-specific basis. The *Standard* is vague on the details for scaling earthquake records to match target spectra, and on how the two horizontal components of these records should be oriented and applied to the model (e.g., to address torsion due to accidental mas eccentricity, etc.).

This slide concludes the part of the presentation that has addressed equivalent lateral force (ELF) design methods, modeling and analysis of the isolation system and dynamic lateral response analysis procedures. The next part of the presentation will apply these methods and procedures to an example design.

Emergency Operations Center Design Example Overview

- Design example illustrates the following:
  - Determination of seismic design parameters
  - Preliminary design using ELF procedures
  - Final design (design verification using dynamic analysis)
  - Specification of isolation system testing criteria
- Hypothetical emergency operations center (EOC)
  - Essential Facility - Risk Category IV
  - High Seismic Site – 6 km from an active fault (SDC F)
  - Configuration – approx. 50,000 sf, 3-stories plus mechanical penthouse with helipad
  - Structure - Steel special concentric braced frames
  - Isolators – Double-concave FPS sliding bearings (35 isolators)

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The design example is a hypothetical 3-story (plus mechanical penthouse) emergency operations center (EOC), assumed to be located in Oakland, California, approximately 6 kilometers from the Hayward fault (i.e., high seismic location). Seismic isolation is an appropriate design strategy for EOCs and other essential facilities where the goal is to limit earthquake damage and protect facility function.

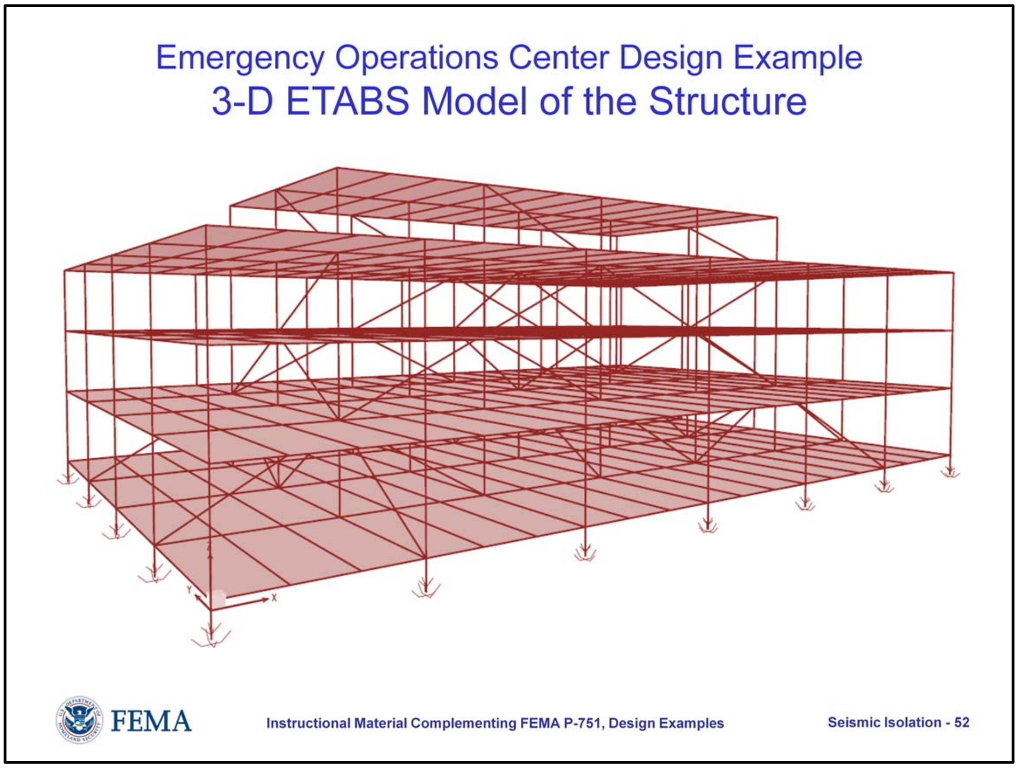
Steel special concentric braced frames are used for the seismic force resisting system. Steel braced frames are commonly used for structure isolated buildings, although other systems could have been used in this example. The isolation system incorporates double-concave friction pendulum sliding bearings, although other types of isolators could have been used in this example.

Emergency Operations Center Design Example Structural Design Criteria – Special SCBF

- Height limit (Table 12.2-1, SDC F) — h < 100 ft
- Response modification factor (R and R_I):
  - Fixed-base (Table 12.2-1): — R = 6
  - Isolated (Sec. 17.5.4.2): — R_I = 2 (C_d = 2)
- Importance factor, I_e (Risk Category IV):
  - Fixed-base (Sec. 11.5.1/Table 1.5-2): — I_e = 1.5
  - Isolated (Sec. 17.2.1): — I_e = 1.0
- Plan irregularity of superstructure (Table 12.3-1): — None
- Vertical irregularity of superstructure (Table 12.3-2): — None
- Lateral response procedure (Sec. 17.4.1, S_1 > 0.6g): — Dynamic Analysis
- Redundancy factor, ρ:
  - Fixed-base (Table 12.3.4): — ρ > 1.0
  - Isolated (inferred): — ρ = 1.0

FEMA Instructional Material Complementing FEMA P-751, Design Examples — Seismic Isolation - 51

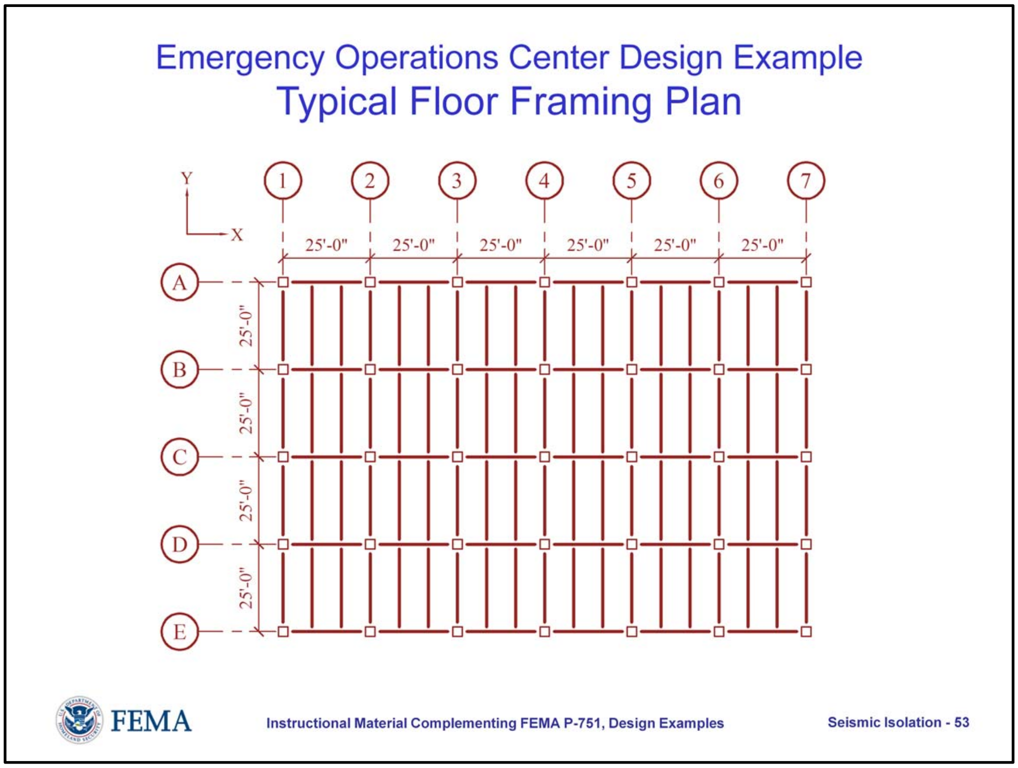
This slide summarizes pertinent structural design criteria for the example EOC. Of note, *Standard* Section 17.5.4.2 specifies I_e = 1.0 for design of an isolated structure, regardless of the risk category. If the EOC was not isolated (fixed-base design), then the value of the importance factor would have been of I_e = 1.5, the value required by Table 1.5-2 of the *Standard* for design of an “essential” (Risk Category IV) structures. Due to the proximity of the site to the Hayward fault (i.e., $S_1 \geq 0.6$g) dynamic analysis is required. In this example, however, the design is first developed using ELF methods and then verified using RHA. The redundancy factor is taken as ρ = 1.0, although a larger value would be required by the *Standard* if the structure was not isolated.



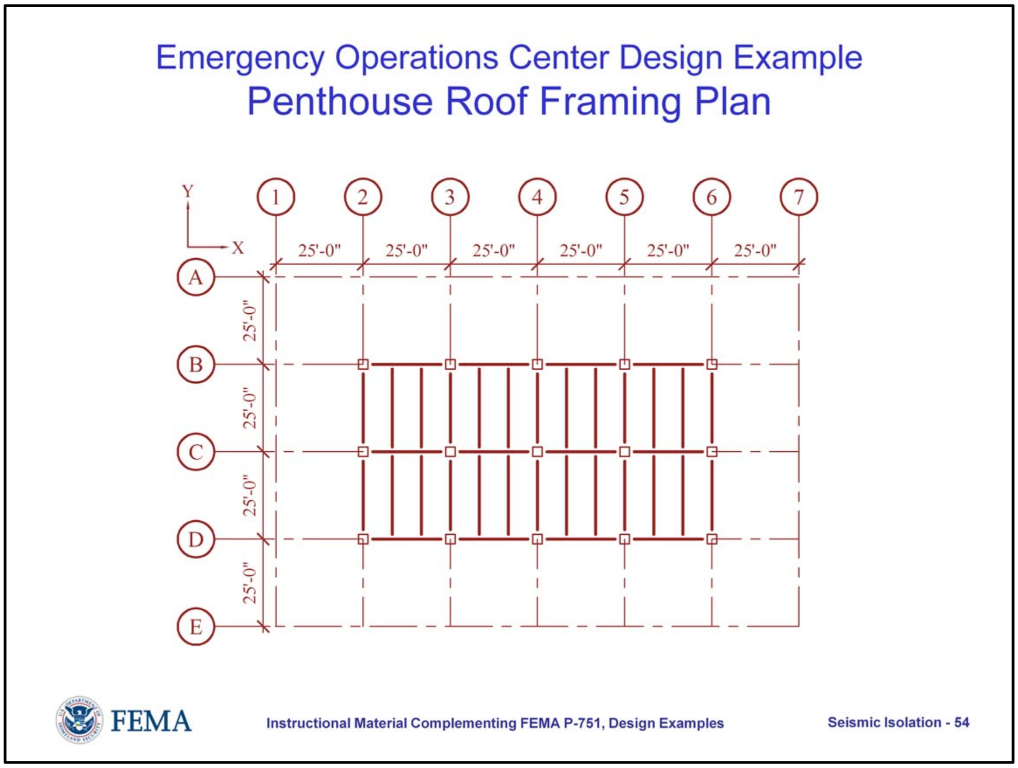
This figure shows the 3-dimensional ETABS model of structure of the EOC building. The ETABS computer program (Computer Structures Inc.) was selected for performing static and dynamic analyses of the isolated structure since this software package has a number of isolation-friendly features, although other commercially available structural analysis programs could have been used.

The ETABS model was used to perform the following analyses:

1. Gravity Load Evaluation – Distribution of building weight on isolators
2. ELF – Gravity and earthquake load design of the superstructure
3. Pushover analysis (ELF loads) – Distribution of gravity and earthquake (design earthquake and MCE_R) loads on isolators (and foundations)
4. RHA – Peak design earthquake and MCE_R displacement of the isolation system and peak design earthquake and MCE_R story shear

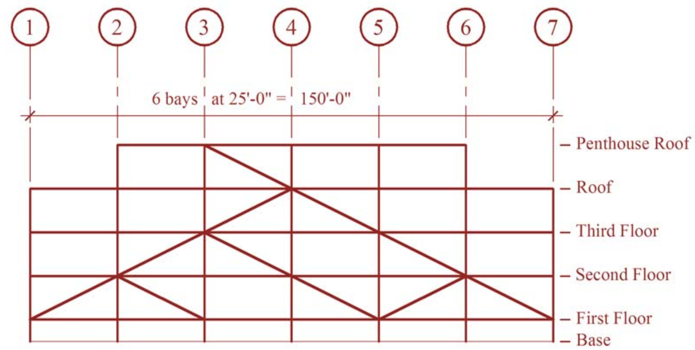


This figure is a plan view showing typical floor framing - 4 bays x 6 bays, columns at 25 feet, on center.



This figure is a plan view showing penthouse roof framing.

Emergency Operations Center Design Example
Longitudinal Bracing Elevation



Lines B and D

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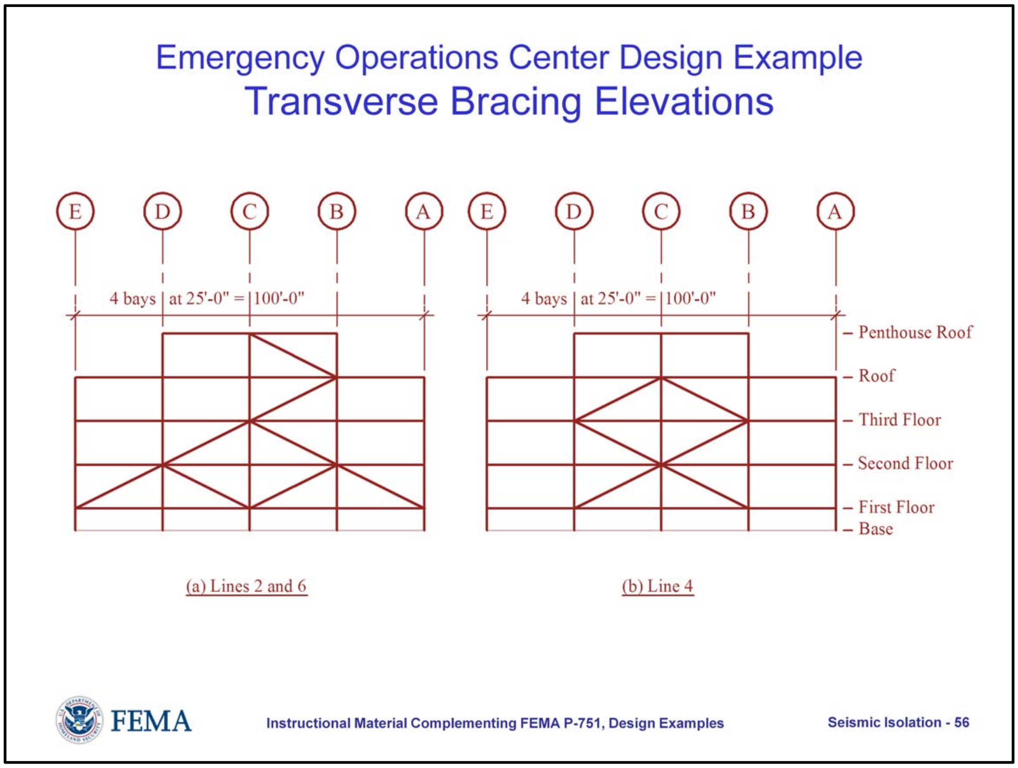
This figure an elevation view showing longitudinal bracing on Lines B and D



This figure shows transverse bracing on Lines 2, 4 and 6

Emergency Operations Center Design Example
Basic Design Requirements

- Seismic Codes and Standards
  - General: ASCE 7-05 (*Standard*)
  - Seismic: 2009 NEHRP Recommended Provisions
  - Other Loads (load combinations): 2006 IBC
- Materials
  - Concrete: floor slabs $f_c' = 3$ ksi
    - foundations $f_c' = 5$ ksi
    - normal weight 150 psf
  - Steel: columns $F_y = 50$ ksi
    - primary girders (1st-floor) $F_y = 50$ ksi
    - other girders and beams $F_y = 36$ ksi
    - braces $F_y = 46$ ksi
  - Steel Deck 3-inch deep, 20-gauge deck

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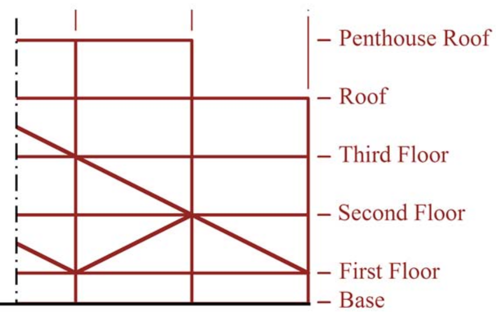
This slide summarizes basic design requirements, governing codes and material properties. Note. Example EOC design was developed in accordance with the 2006 IBC (and by reference ASCE 7-05) except for seismic requirements which were based on new ground motions and other earthquake provisions of the 2009 NEHRP *Provisions* (which are essentially the same as those of ASCE 7-10)

Emergency Operations Center Design Example

Gravity Loads (by elevation)

Elevation	Load	Kips
Penthouse Roof	W_{PR}	794
Roof	W_R	2,251
3rd Floor	W_3	1,947
2nd Floor	W_2	1,922
1st Floor	W_1	2,186
Total Weight	W	9,100
Total Live	L	5,476
Reduced Live	L	2,241



Total dead load (D) weight on isolators

Total unreduced live load

Total reduced live load (L) weight on isolators

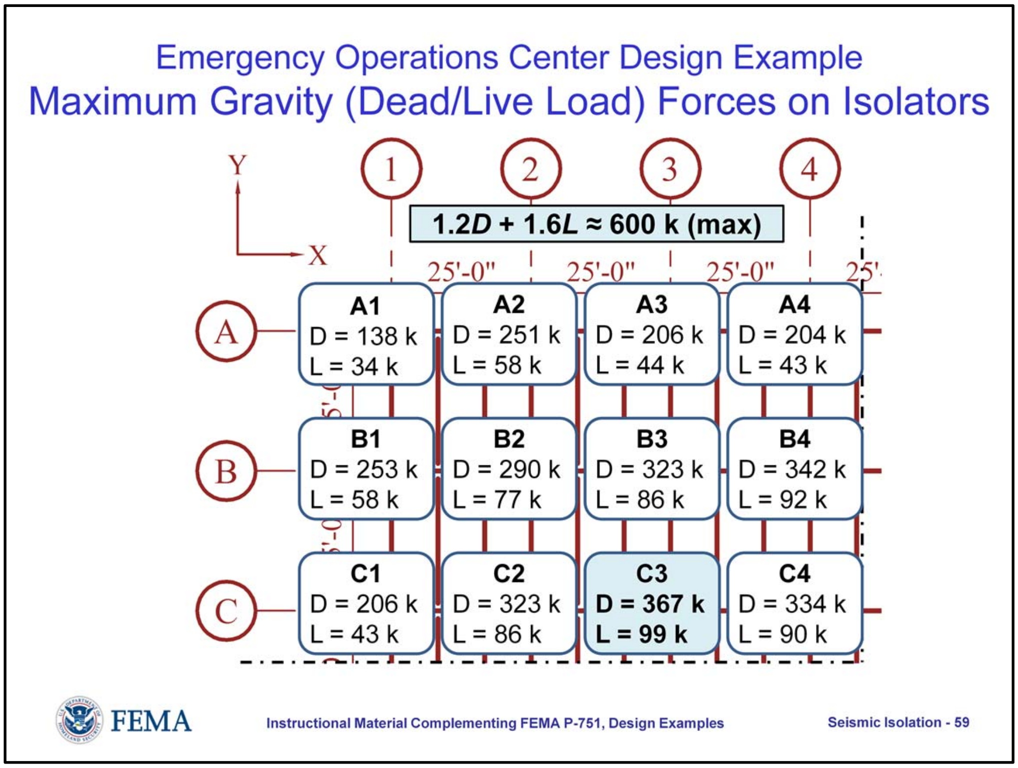
Instructional Material Complementing FEMA P-751, Design Examples

Seismic Isolation - 58

The weight of each floor and distribution of the total weight on isolators must be determined as a necessary first step in the design of the isolation system.

This figure shows the dead load (seismic) weight of gravity loads by floor level. The total dead load (seismic) weight on isolators is 9,100 kips with an additional reduced live load weight on isolators is 2,241 kips. Seismic weight is used for lateral force design and analysis. Additional reduced live loads must be included for gravity load design of isolators.

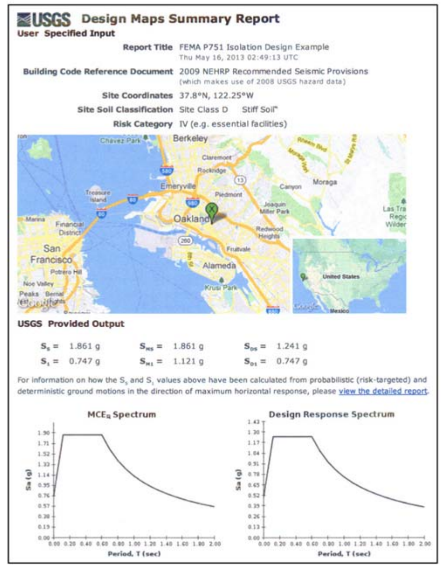
Although isolators must be design for additional requirements (e.g., MCE_R loads), the same basic load combinations (e.g., long-term gravity design loads) that apply to columns of building also apply to the design of isolators.



This figure shows a plan view of one quadrant of the EOC building at the 1st-floor. This plan view is used in this slide and in subsequent slides to show the values of loads on individual isolators. Due to building symmetry, loads on isolators in other quadrants are very similar (click). Values of dead load (D) and reduced live load (L) are shown at each isolator location (click). Long-term gravity design loads on isolators are defined by 1.2D + 1.6L load combination of the 2006 IBC. Long-term design loads on isolators range from about 220 kips at corner isolators (A1) to about 600 kips at an interior isolator (C3). The maximum value of long-term design load is an important parameter for preliminary design of bearing sizes.

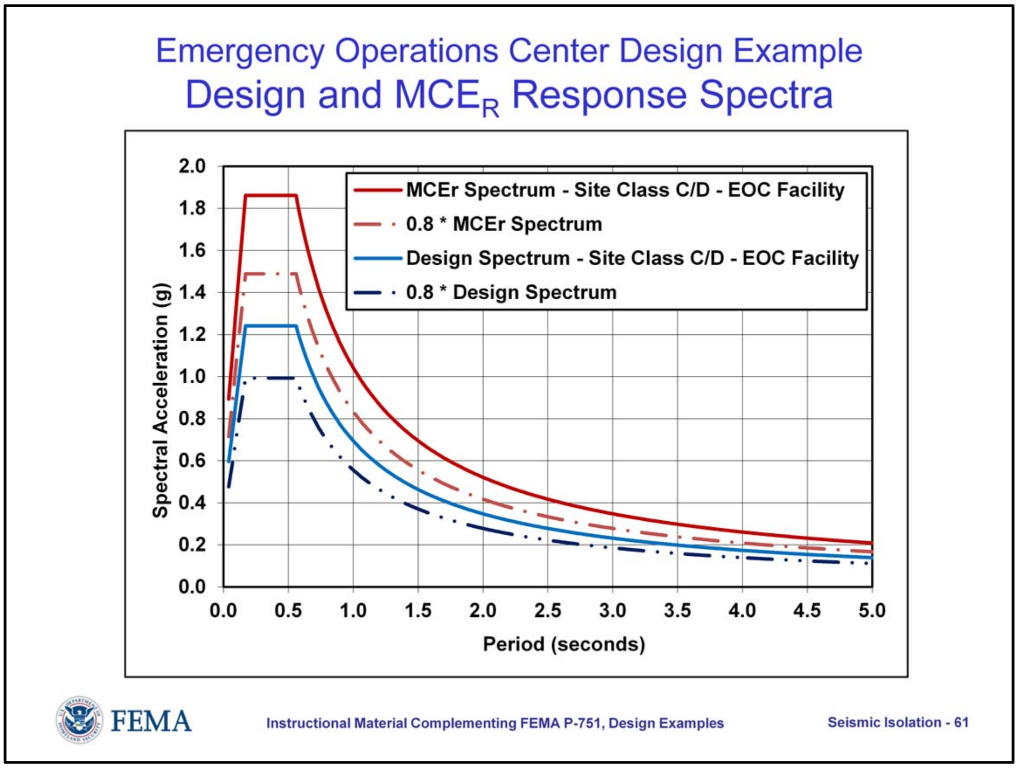
Emergency Operations Center Design Example
Seismic Design Parameters (USGS)

- Design Parameters at USGS website: http://geohazards.usgs.gov/designmaps/
- User enters design data:
  - Code: 2009 NEHRP Provisions
  - Site Classification: Site Class C or D
  - Risk Category: Risk Category IV
  - Site Lat. 37.80^0 Site Long. - 122.25^0
- Summary report provides:
  - Echo print of design data
  - Map showing site location
  - MCE_R and design ground motions:
    - S_{MS} = 1.861 g; S_{DS} = 1.241 g
    - S_{M1} (D) = 1.121 g; S_{D1} = 0.747 g
    - S_{M1} (C) = 0.972 g; S_{D1} = 0.648 g
  - Plots of MCE_R and Design Spectra
  - Supporting Data (long report)



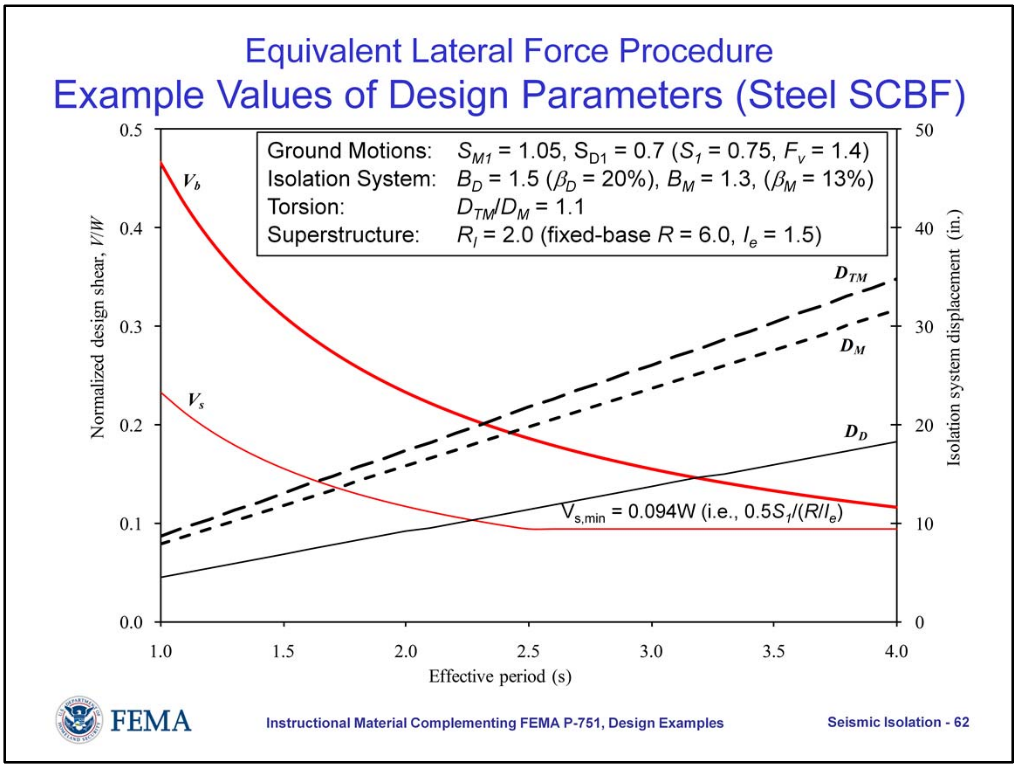
The seismic design parameters must be determined for the site of interest. Fortunately, the USGS has developed a website that provides values of these parameters for various editions of Seismic Codes, including the 2009 NEHRP *Provisions* (and ASCE 7-10).
Users of the USGS website enter the name of the governing Seismic Code, the site classification (e.g., from a geotechnical study of the site), the risk category of the building and latitude and longitude of the building site (e.g., the example EOC is assumed to located at Lat. 37.80^0 and Long. - 122.25^0.
The website returns a report (summary report is shown in this slide) including values of the seismic design parameters for the site of interest. In this example, the site is classified as "CD" and seismic design parameters are taken as the average of the USGS values for Site Class C and Site Class D.

Note. The design parameters at short-periods given in Chapter 12 FEMA P-751 erroneously used two-thirds of the values shown in this slide (which does not effect the design example, other than the value of the vertical component ground motions in load combinations).

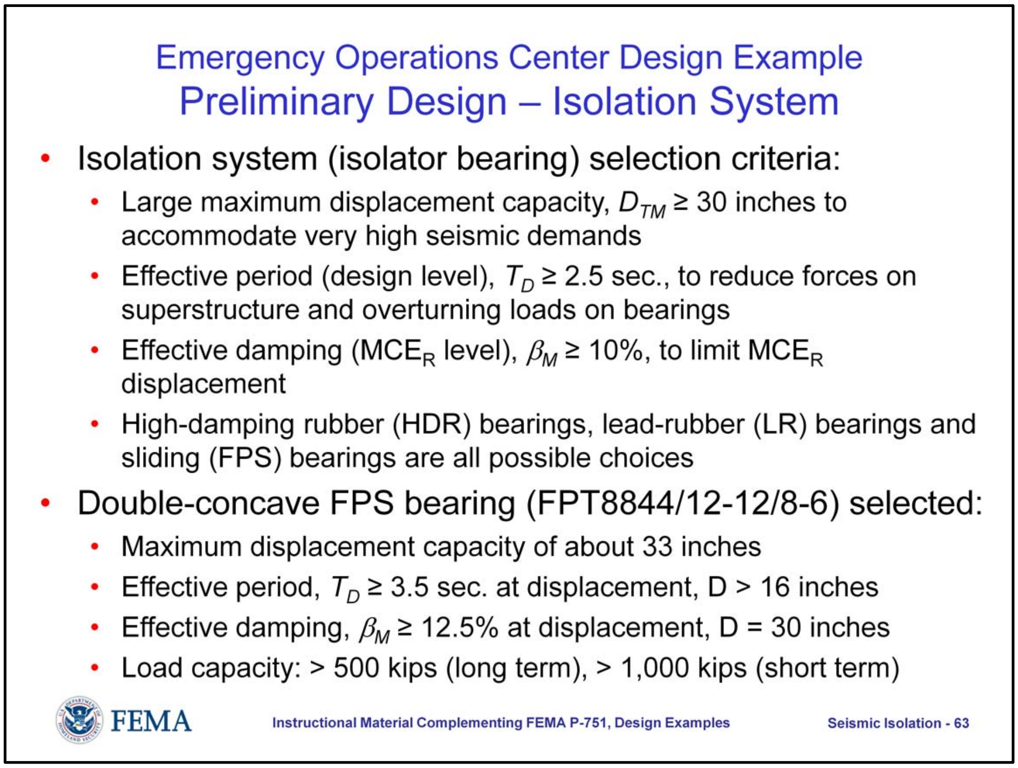


This figure shows design earthquake and MCE_R response spectra for the EOC site. These spectra are constructed in accordance with the procedure of Section 11.4 of the *Provisions (*and the generic spectrum shape of Figure 11.4-1) and the seismic design parameters obtained for the USGS web site.

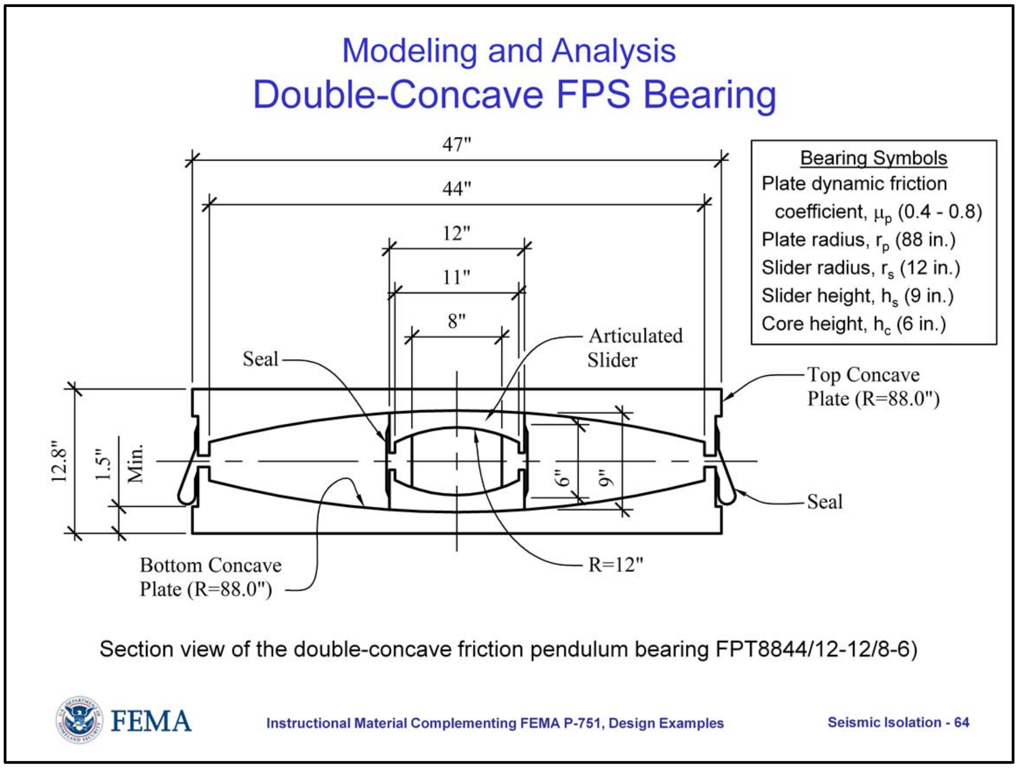
As note previously, site-specific ground motions (site-specific spectra) are required for design of isolated structures when $S_1 \geq 0.6$ which is the case for example EOC. This was not done for this example, rather the generic spectra shown in this figure were used in lieu of site-specific spectra. Subject to other limitations, site-specific spectra can be taken as less than 100 percent, but not less than 80 percent of generic spectra shown in the figure. For this example, site-specific spectra were conservatively taken as 100 percent of generic spectra shown in this figure.



Preliminary design of the isolation system requires selection of one or more candidate isolator bearing types that have sufficient load and displacement capacity to meet project requirements. The formulas of the ELF procedure may be used with site seismic design parameters to develop appropriate selection criteria, as illustrated in this slide (copy of Slide 35). While there is no precise "right" set of criteria, this slide suggests that isolators will require large (e.g., > 30 inch) displacement capacity to accommodate MCE_R displacements (D_{TM}), if unreduced lateral force (V_b) on the isolated structure is limited to 0.15W – 0.2W. The figure also shows that the design base shear for the superstructure (V_s) is the same for design periods (T_D) greater than about 2.5 seconds (i.e., better performance, but no structure design economy design periods longer then 2.45 seconds).



This figure summarizes isolation system selection criteria based on the curves shown in the preceding slide.
High-damping rubber (HDR), lead-rubber (LR) and sliding (FPS) isolator bearings could all be configured to meet these criteria.
For this example, the double-concave FPS bearing (FPT884412-12/8-6) was selected for use at each of the 35 isolator locations. This bearing has a relatively long period (T_D > 3.5 seconds) which helps to limit lateral forces and related overturning loads, and potential uplift of individual isolators below braced frames. One isolator bearing size is convenient, but typically (and especially for elastomeric bearings), isolated structures use more than one type of isolator bearing based on the amount of vertical load supported by the bearing.



This figure is a section view of the double-concave FPS bearing used in this example. This bearing utilizes an articulated slider between the top and bottom concave plates (dishes). For this example double-concave application, the nominal value of dynamic friction is the same for top and bottom concave plates such that total displacement is “symmetric” and shared approximately equally between the top and the bottom concave plates. Other configurations of this bearing (i.e., triple-pendulum bearings) utilize different nominal values of dynamic friction for the top and bottom plates which affect a more complex “asymmetric” pattern of total displacement.

Emergency Operations Center Design Example
Seismic Force Analysis – ETABS Model

- A linear, 3-D (ETABS) model of the EOC structure was used to expedite calculation of the following loads and load combinations:
  - Gravity loads, including maximum long-term loads on isolators:
    - 1.2D + 1.6L
  - Superstructure design forces for combined gravity and reduced design earthquake load effects ignoring potential uplift of isolators (pushover using ELF lateral forces):
    - $1.2D + 0.5L + E = (1.2 + 0.2S_{DS})D + 0.5L + Q_{DE/2}$
    - $0.9D – E = (0.9 – 0.2S_{DS})D - Q_{DE/2}$
  - Isolation system and foundation design forces for combined gravity and unreduced design earthquake loads and permitting local uplift of individual isolator units (pushover using ELF lateral forces):
    - $1.2D + 0.5L + E = (1.2 + 0.2S_{DS})D + 0.5L + Q_{DE}$
    - $0.9D – E = (0.9 – 0.2S_{DS})D - Q_{DE}$

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This slide summarizes ETABS gravity and seismic force analyses and related load combinations required for design of the example EOC. Reduced design earthquake loads are used in load combinations for design of the superstructure. Unreduced design earthquake loads are used in load combinations for design of the isolation system, and foundation elements below.

Emergency Operations Center Design Example
Seismic Force Analysis – ETABS Model

- A linear, 3-D (ETABS) model of the EOC structure was used to expedite calculation of the following loads and load combinations:
  - Maximum short-term (downward) and minimum short-term (downward) forces on individual isolators for combined gravity and unreduced design earthquake loads (pushover using ELF lateral forces and permitting local uplift of individual isolators)
    - $1.2D + 1.0L + E = (1.2 + 0.2S_{MS})D + 1.0L + Q_{DE}$
    - $0.9D – E = (0.9 – 0.2S_{MS})D - Q_{DE}$
  - Maximum short-term (downward) and minimum short-term (maximum uplift displacement) forces on individual isolators for combined gravity and unreduced MCE_R loads (pushover using ELF lateral forces and permitting local uplift of individual isolators)
    - $1.2D + 1.0L + E = (1.2 + 0.2S_{MS})D + 1.0L + Q_{MCE}$
    - $0.9D – E = (0.9 – 0.2S_{MS})D - Q_{MCE}$

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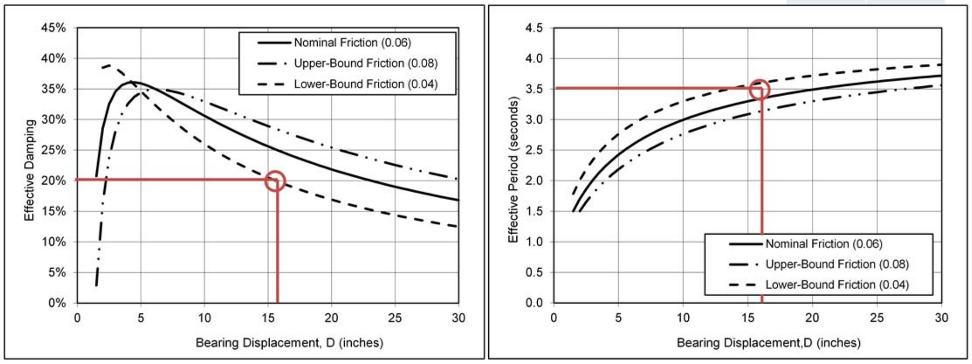
This slide summarizes ETABS pushover analyses and related load combinations used to determine maximum and minimum short-term forces on individual isolators due to the design earthquake loads and maximum short-term (downward forces) and minimum short-term (maximum uplift displacements) on individual isolators due to MCE_R loads. These forces (and displacements) are used for design of isolators and for establishing load criteria for prototype testing of isolator units.

Emergency Operations Center Design Example
Preliminary Design – ELF Displacement

- Design Displacement, D_D:

$$D_D = \left(\frac{g}{4\pi^2}\right)\frac{S_{D1}T_D}{B_D} = (9.8)\frac{0.7(3.5)}{1.5} = 16.0 \text{ in.}$$

B_D, B_M	β_D, β_M
1.2	10%
1.35	15%



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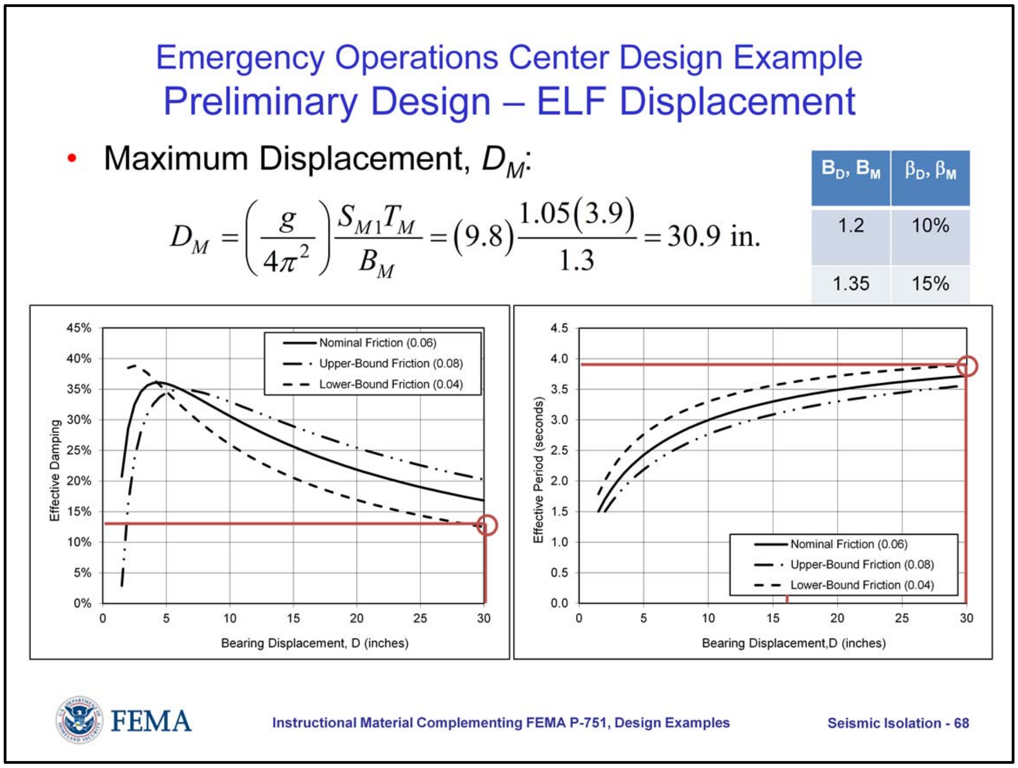
The next sequence of eight slides illustrates preliminary design of EOC using the formulas of the ELF procedure and site seismic parameters and the effective properties of the double-concave FPS bearing.

In this figure, the design displacement (D_D) is calculated as 16.0 inches, based on an effective period of T_D = 3.5 seconds and an effective damping of β_D = 20% (B_D = 1.5). The effective period and damping parameters are amplitude dependent and the process to determine their values is necessarily iterative. Figures of effective period and damping as a function of double-concave FPS bearing displacement shown in this slide (i.e., figures shown previous as Slides 42 and 43) are used to expedite the process. As shown by the red lines, an effective period of T_D = 3.5 seconds and an effective damping of β_D = 20% correspond to about 16 inches of displacement of the double concave FPS bearing.



In this figure, the maximum displacement (D_M) is calculated as about 31 inches, based on an effective period of T_D = 3.9 seconds and an effective damping of β_D = 13% (B_D = 1.3). The effective period and damping parameters are amplitude dependent and the process to determine their values is necessarily iterative. Figures of effective period and damping as a function of double-concave FPS bearing displacement shown in this slide (i.e., figures shown previous as Slides 42 and 43) are used to expedite the process. As shown by the red lines, an effective period of T_D = 3.9 seconds and an effective damping of β_D = 13% correspond to about 30 inches of displacement of the double concave FPS bearing.

Emergency Operations Center Design Example
Preliminary Design – ELF Displacement

- Total Design and Maximum Displacements, D_{TD} and $D_{TM,}$ (e = 0.05d):

$$D_{TD} = DD\left[1 + y\frac{12e}{b^2+d^2}\right] = 16\left[1 + 90\left(\frac{12(0.05)150}{100^2+150^2}\right)\right] = 16\ (1.25)$$

$$D_{TM} = DM\left[1 + y\frac{12e}{b^2+d^2}\right] = 30.9\left[1 + 90\left(\frac{12(0.05)150}{100^2+150^2}\right)\right] = 30.9\ (1.25)$$

- FPS bearings mitigate the effects of mass eccentricity, but additional displacement due to actual plus accidental torsion cannot be taken as less than 1.1 times translation-only displacement which corresponds to e = 0.02d for the geometry of the EOC building:

$$D_{TD} = DD\left[1 + y\frac{12e}{b^2+d^2}\right] = 16\left[1 + 90\left(\frac{12(0.02)150}{100^2+150^2}\right)\right] \geq 16\ (1.1) = 17.6\ in.$$

$$D_{TM} = DM\left[1 + y\frac{12e}{b^2+d^2}\right] = 30.9\left[1 + 90\left(\frac{12(0.02)150}{100^2+150^2}\right)\right] \geq 30.9\ (1.1) = 34\ in.$$

This slide illustrates the ELF formulas used to calculate "total" design and maximum isolation system displacement where "total" means displacement (at corners) due to both translation and rotation due to actual plus accidental mass eccentricity. Amplification of translation-only displacement is based on plan geometry and the assumption that isolator stiffness is distributed in plan proportional to supported weight. For the example EOC, the formulas suggest a 25 percent increase in displacement due to rotation. The Standard permits using a smaller amount displacement amplification, but not less than 10 percent, provided such can be justified. In the case of sliding isolators, the "stiffness" of the bearing is approximately proportional to the weight supported, effectively reducing the potential for rotation due to accidental mass eccentricity. On this basis, the example EOC is designed for the minimum 10 percent increase in displacement and the total maximum displacement (DTM) of a corner of the example EOC is 34 inches (approximately the displacement capacity of the double-concave bearing).

Emergency Operations Center Design Example

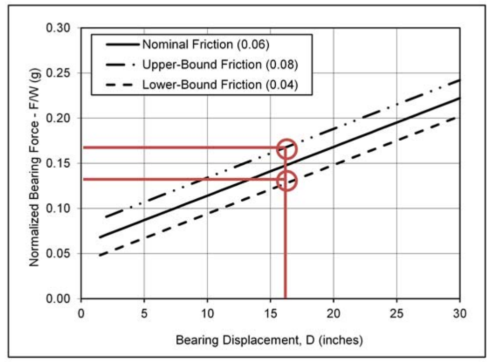
Preliminary Design – ELF Effective Stiffness

- Minimum and Maximum Effective Design Stiffness:

$$k_{D\min} = \left(\frac{4\pi^2}{g}\right)\frac{W}{T_D^2} = \left(\frac{1}{9.8}\right)\frac{9{,}100}{3.5^2} = 75.8 \text{ kips/in.}$$

Maximum effective stiffness is estimated to be about 1.2 times minimum effective displacement at the maximum displacement, D_D = 16 inches

$$k_{D\max} = 1.2(75.8) = 91.0 \text{ kips / in.}$$



FEMA Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 70

In this figure, the minimum value of effective design stiffness is calculated for T_D = 3.5 seconds and W = 9,100 kips, and the maximum value of effective stiffness is estimated as 1.2 times the minimum value (by comparing normalized bearing force at 16 inches, as shown in the figure). ELF formulas use maximum effective stiffness to calculate lateral design force. This approach, originally developed for elastomeric bearings also works for sliding bearings, recognizing that the stiffness is related to weight on the bearing (since the friction force is proportional to the weight supported).

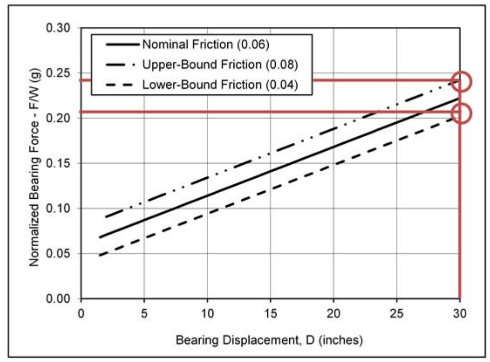
Emergency Operations Center Design Example
Preliminary Design – ELF Effective Stiffness

- Minimum and Maximum Effective MCE$_R$ Stiffness:

$$k_{M\,\min} = \left(\frac{4\pi^2}{g}\right)\frac{W}{T_D^2} = \left(\frac{1}{9.8}\right)\frac{9{,}100}{3.9^2} = 61.1\ \text{kips/in.}$$

Maximum effective stiffness is estimated to be about 1.15 times minimum effective displacement at the maximum displacement, D_M = 30.9 inches

$$k_{M\,\max} = 1.15(61.1) = 70.3\ \text{kips / in.}$$



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In this figure, the minimum value of effective stiffness at MCE$_R$ displacement is calculated for T_M = 3.9 seconds and W = 9,100 kips, and the maximum value of effective stiffness at MCE$_R$ displacement is estimated as 1.15 times the minimum value (by comparing normalized bearing force at 30 inches, as shown in the figure). Maximum effective stiffness at MCE$_R$ displacement is used to calculate MCE$_R$ forces on the isolation system.

Emergency Operations Center Design Example

Preliminary Design – ELF Lateral Design Force

- Design of the Isolation System, foundation and structure below:

  $V_b = k_{Dmax}\, D_D = 91.0(16.0) = 1{,}456 \text{ kips}$ 0.16W

- Stability check of Isolation System for MCE_R response:

  $V_{MCE} = k_{Mmax}\, D_M = 70.3(30.9) = 2{,}172 \text{ kips}$ 0.24W

- Design of the structure above the Isolation System:

  $V_s = \dfrac{k_{D\max}\, D_D}{R_I} = \dfrac{91.0(16.0)}{2.0} =$ ~~728 kips~~ ~~0.08W~~

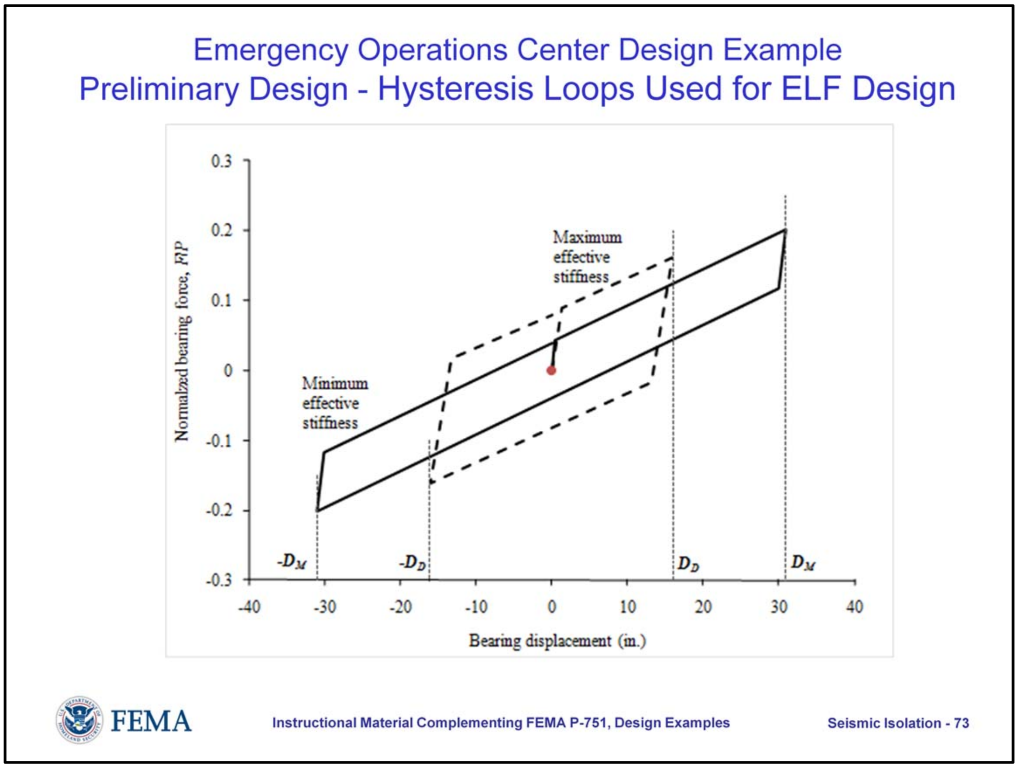
  $V_s = 0.5S_1/(R/I_e) = 0.5(0.75)/(6/1.5) =$ ~~853 kips~~ ~~0.094W~~

  $V_s = 1.5\,\mu_{P,\max}\, W = 1.5(0.08)9{,}100 = 1{,}092 \text{ kips}$ 0.12W

FEMA Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 72

This figure illustrates the calculation of the unreduced shear force (V_b) required for design of the isolation system and the foundation, the calculation of the unreduced shear force at MCE_R displacement used to check the stability of the isolation system, and calculation of the reduced shear force (V_s) required for design of the superstructure. In all cases, shear force is expressed as a fraction of the seismic weight (W).

The shear force required for design of the superstructure is reduced by a factor of 2, subject to other limits of design base shear. Without these limits, the design shear force would be V_b = 0.16W reduced by R_I = 2, or V_s = 0.08W. However, this value of shear force is less than both the minimum force required for design of fixed-base building of period, T_D = 3.5 seconds (i.e., V_s = 0.094W) and the shear force required to activate the isolation system based on maximum value of dynamic friction, $\mu_{P,max}$ = 0.08 (i.e., V_s = 0.12W). Hence, the superstructure of the example EOC building is designed for V_s = 0.12W or 1,092 kips, the isolation system and foundation are designed for V_b = 0.16W, or 1,456 kips, and the stability of the isolation system is checked for V_{MCE} = 0.24W, or 2,184 kips of peak lateral force.



This figure illustrates two of the hysteresis loops implicitly used for ELF design.

The hysteresis loop with plus/minus 31-inch peak displacement (solid line) is based on the minimum value of dynamic friction (0.04), since this results in the largest value of displacement (D_M = 30.9 inches).

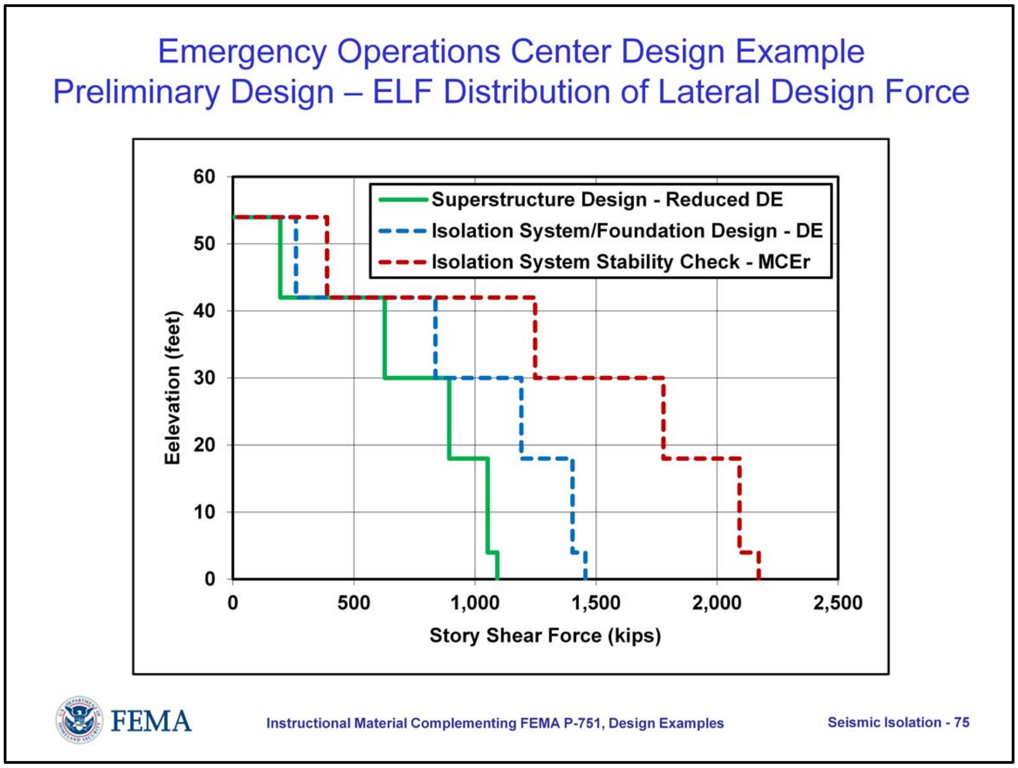
The hysteresis loop with plus/minus 16-inch peak displacement (dashed line) is based on the maximum value of dynamic friction (0.08), since this results in the largest value of design force (V_s = 0.16W).

Note. The design displacement, D_D = 16 inches, was calculated using a value of effective damping, β_D = 20, that was based on minimum dynamic friction (0.04). Thus, ELF forces are conservatively based on maximum effective stiffness, at displacements based on minimum effective stiffness. This is an intentional conservatism of the *Standard* for ELF-based design.

Emergency Operations Center Design Example
Preliminary Design – ELF Distribution of Lateral Design Force

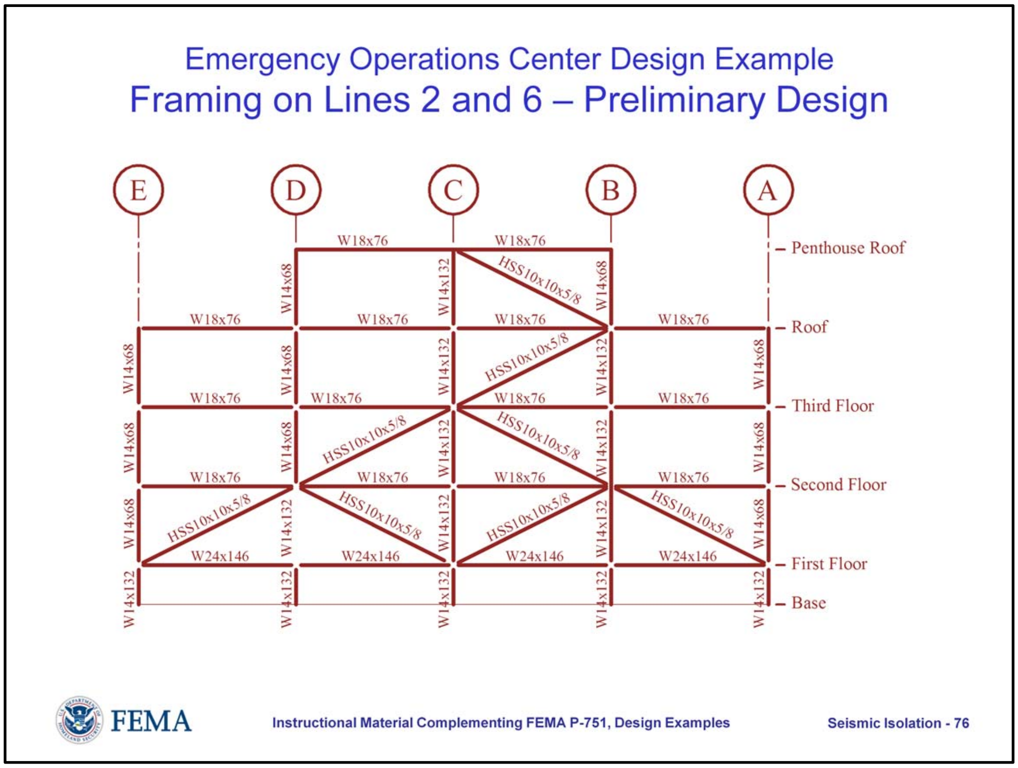
Floor level, x (Story)	Floor weight, w_x (kips)	Cumulative weight (kips)	Height above isolation system, h_x (ft)	Story force, F_x, (kips) (Standard Eq. 17.5-9)	Cumulative story force (kips)	Cum. force divided by cumulative weight
PH Roof	794		54			
(Penthouse)		794		196	196	25%
Roof	2,251		42			
(Third)		3,045		432	628	21%
Third Floor	1,947		30			
(Second)		4,992		267	895	18%
Second Flr.	1,922		18			
(First)		6,914		158	1,053	15%

This figure illustrates the ELF calculation of story forces for the example EOC building using *Standard* Eq. 17.5-9. Height is measured form the isolation interface such that the first floor is 4 feet above the base and the Penthouse (PH) roof is 54 feet above the base of the isolated building. Eq. 17.5-9 is based on an inverted triangular distribution of lateral response with height and the resulting values of cumulative force normalized by cumulative weight at each story may be seen to increase from 12 percent (V_s = 0.12W) at base (isolation interface) to 25 percent at the penthouse level. In general, Eq. 17.5-9 is conservative for isolated structures that have an isolated period that is at least 3 times the period of the structure above the isolation on a fixed base.

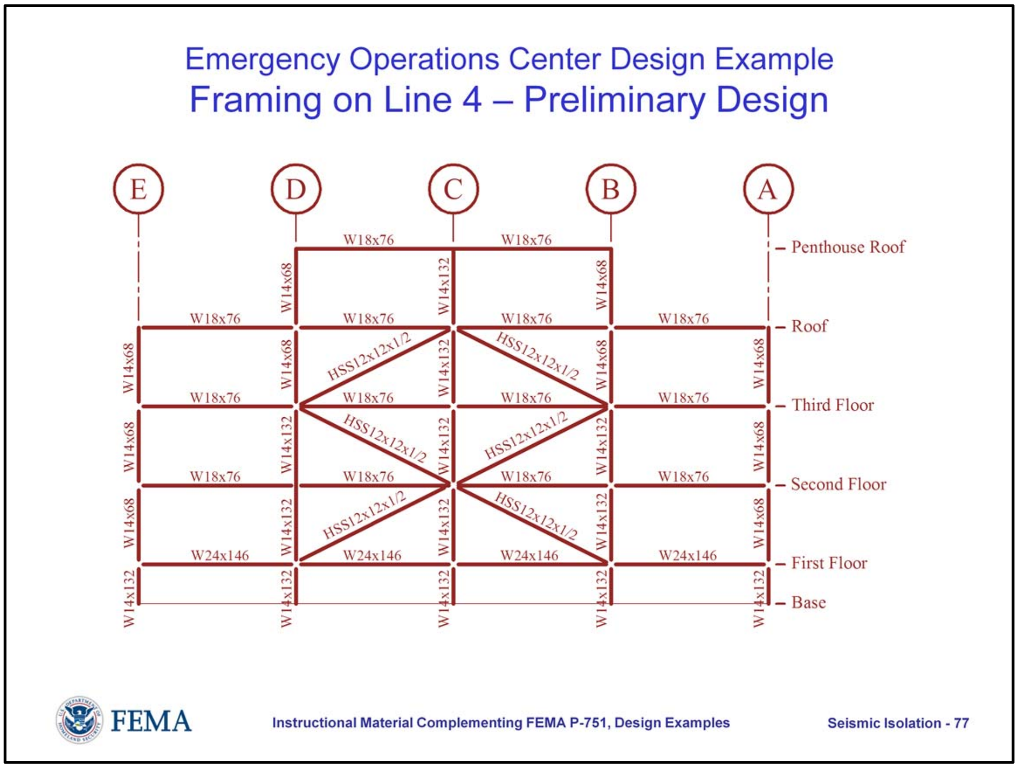


This slide is a figure of the ELF distribution of lateral forces corresponding to:

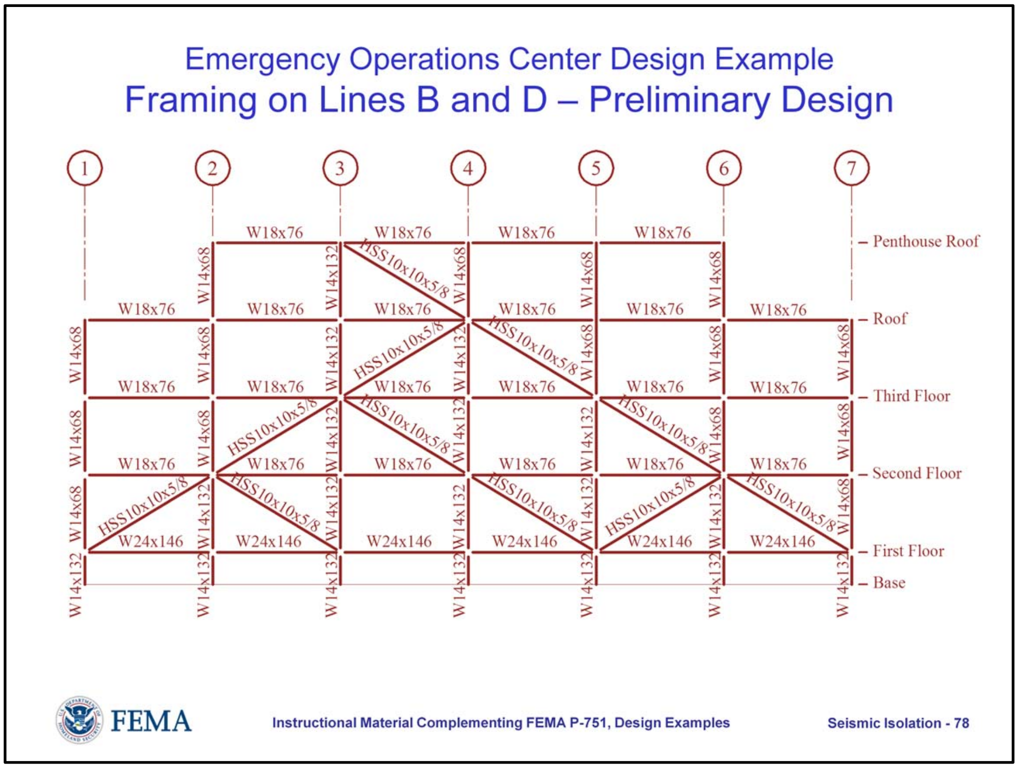
(1) design of the superstructure (reduced design earthquake forces),
(2) design of the isolation system and foundation (unreduced design earthquake forces) and
(3) checking isolation system stability (unreduced MCE_R forces).



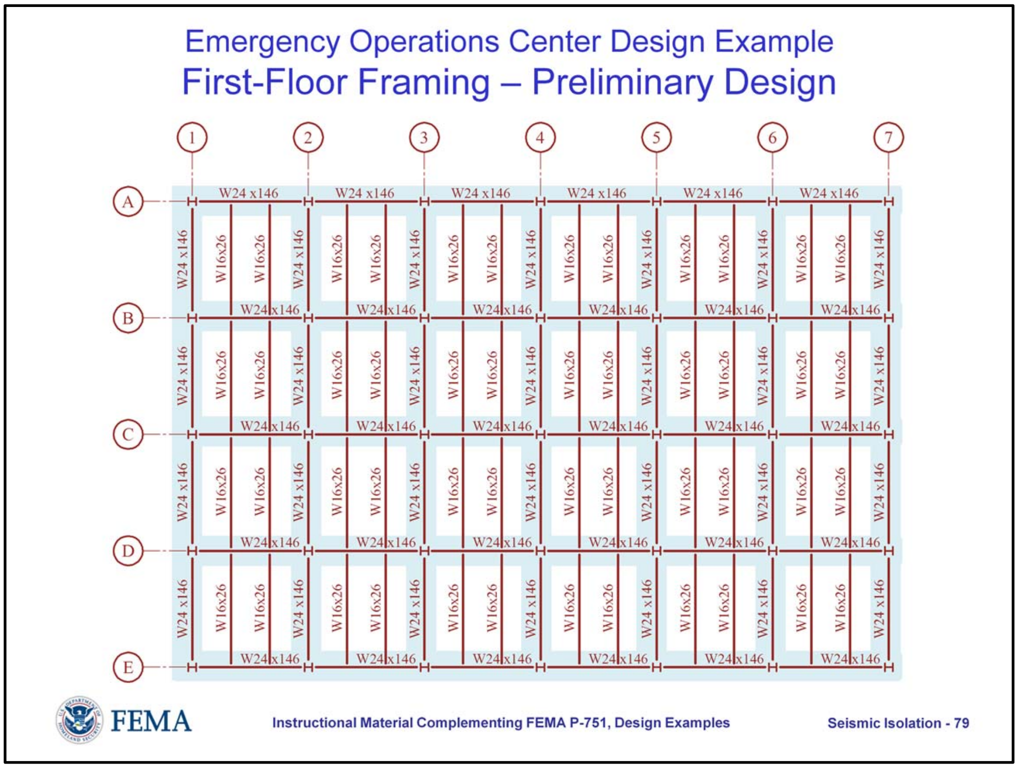
The next four slides show the design of seismic bracing and typical framing based on ELF forces (reduced design earthquake forces).
This first figure shows seismic bracing and typical framing on Lines 2 and 6. Seismic braces are 10-inch square tubes (HSS 10 x 10 x 5/8) at all locations.



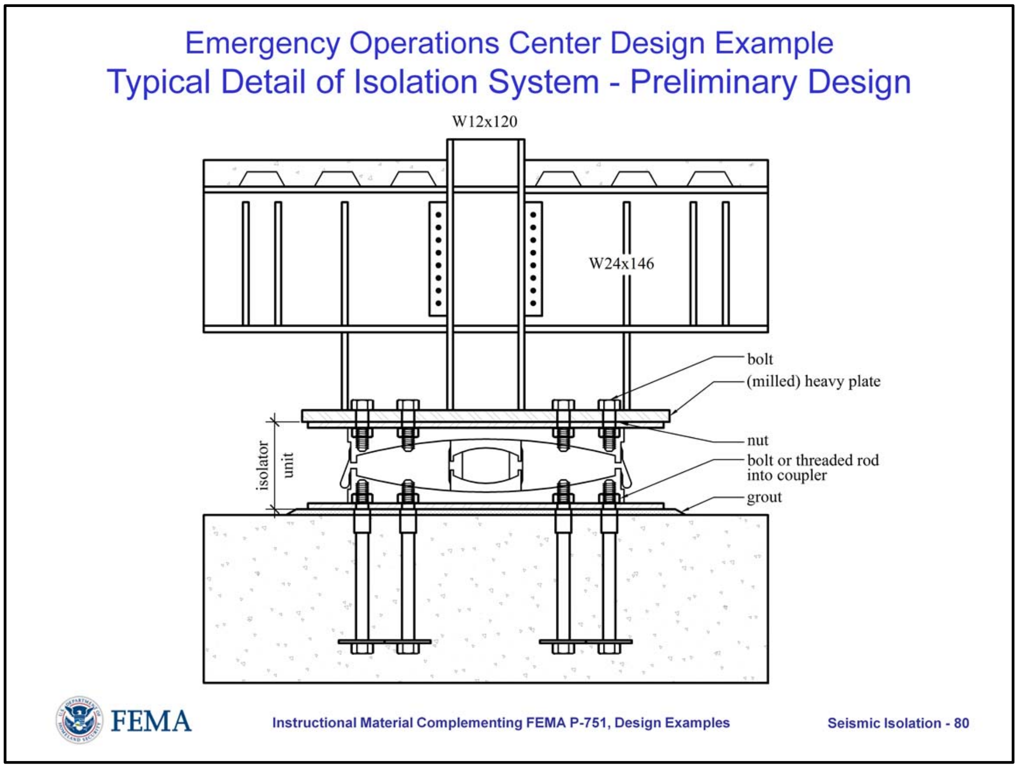
This figure shows seismic bracing and typical framing on Line 4. Seismic braces are 10-inch square tubes (HSS 10 x 10 x 1/2) at all locations.



This figure shows seismic bracing and typical framing on Lines B and D. Seismic braces are 10-inch square tubes (HSS 10 x 10 x 5/8) at all locations.



This figure shows first-floor framing. Blue shading shows heavier W24 x 146 girders on column (isolator) lines where framing is required to resist moments due to P-D loads and horizontal shear in isolators.

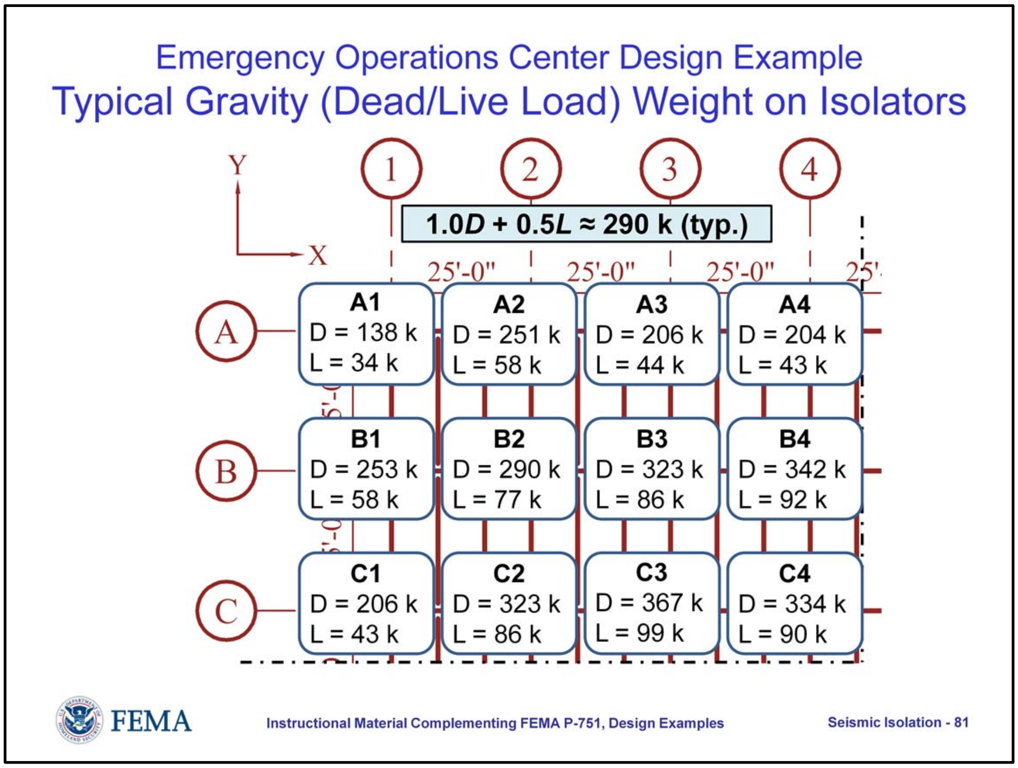


This slide shows a typical detail of the isolation system at an isolator bearing.

The isolator bearing is installed with anchors and grout directly above the top of the reinforced-concrete foundation (rebar not shown). The strength of the grout and the design of reinforced-concrete foundation is governed by loads from bottom plate of the double-concave bearing considering all possible displacements of the articulated slider.

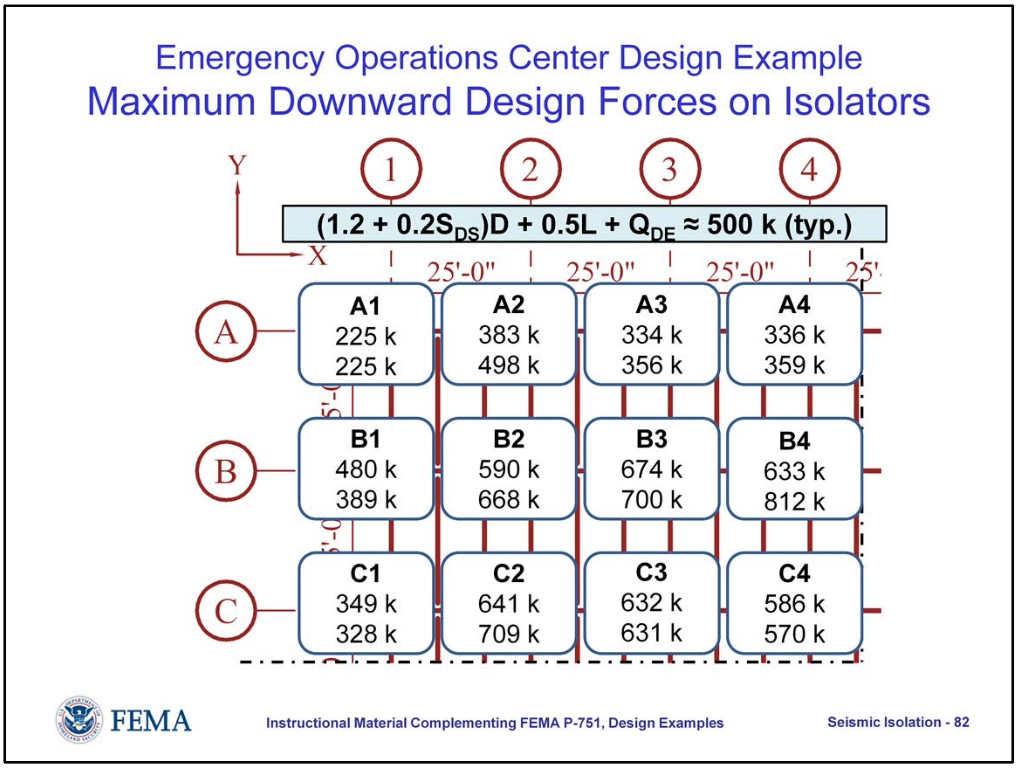
Foundation anchors utilize threaded rods and couplers to permit bearing removal.

The top plate to the bearing bears on a (milled) heavy steel plate attached to the base of the column. Steel sections and stiffeners running from the underside of the girder to the top of the heavy plate are designed to provide stability to the top concave plate of the bearing (again considering all possible displacements of the articulated slider).

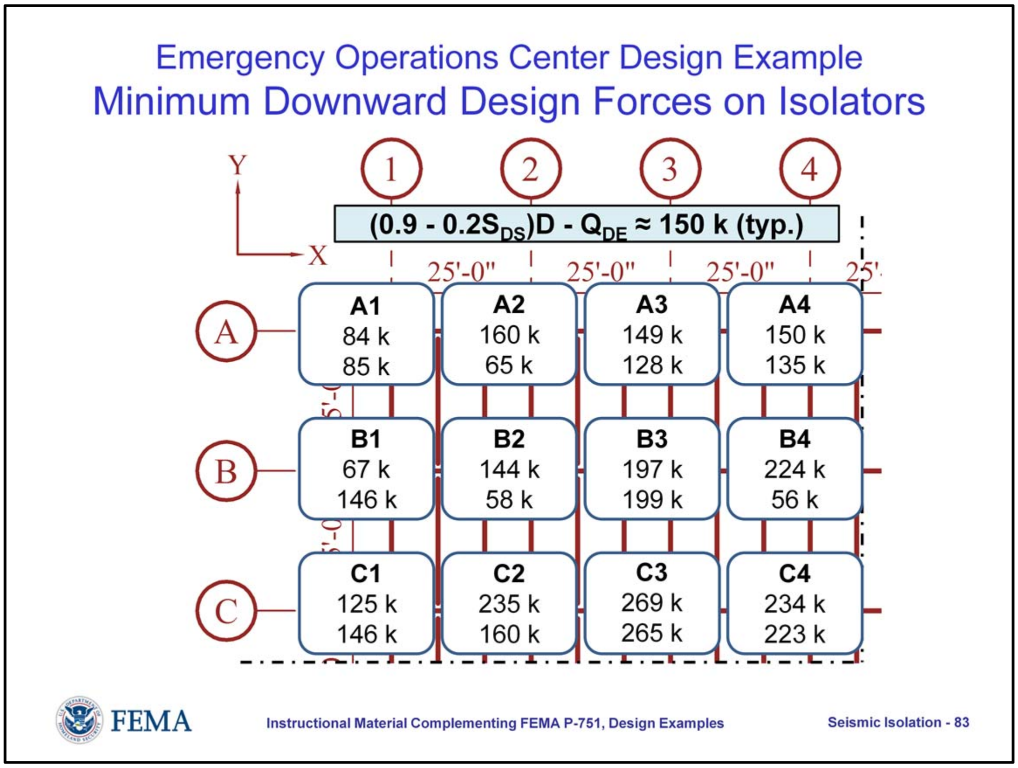


The figure shows typical gravity (dead load and reduced live load) weight on isolator bearings (same loads shown previously in Slide 58). Based on the load combination, 1.0D + 0.5L, weight on individual bearings varies from about 150 kips to about 400 kips and the typical, or average weight, supported by all bearing is about 290 kips (i.e., 35 bearings x 290 kips/bearing = 10,150 kips) and the.

The typical weight on isolators (i.e., without load factors) is used for prototype testing of isolator units.

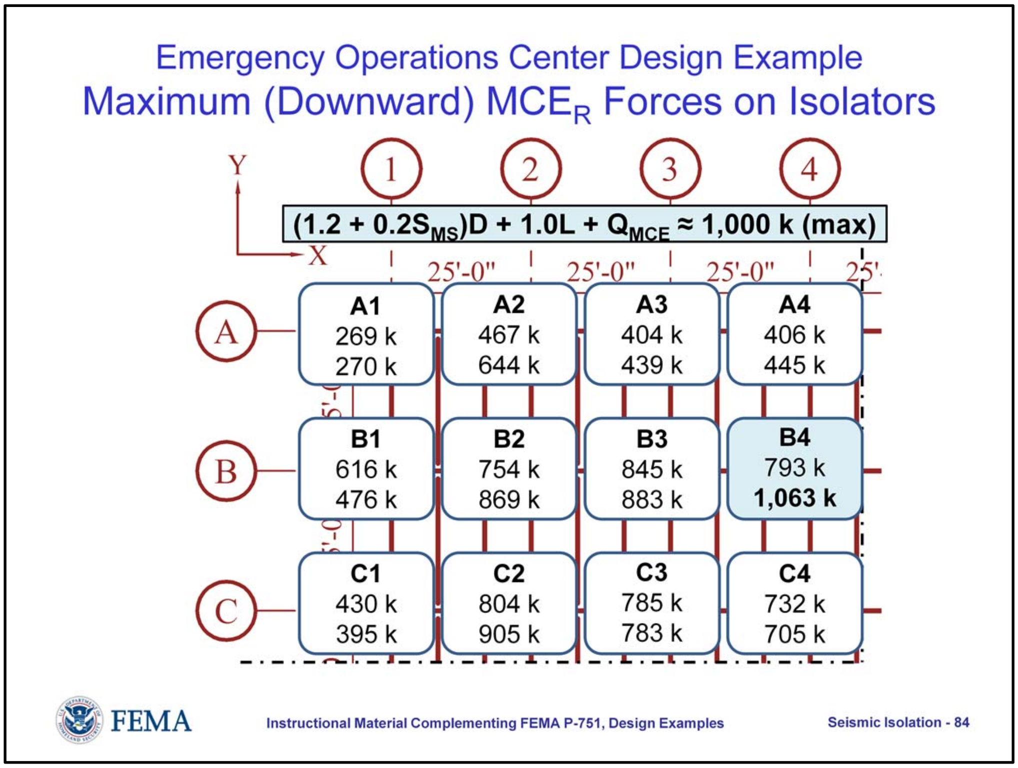


The next four slides summarize forces on (or uplift displacements of) individual isolator bearings due to dead, live and seismic (overturning) loads for different load combinations. Seismic (overturning) loads on individual bearings were calculated by pushover analysis using ELF lateral seismic loads. Forces (or uplift displacements) are shown for both the X and Y direction of earthquake response (i.e., direction of the pushover).
The first figure shows maximum downward gravity and design earthquake forces on isolators, based on the load combination, $(1.2D + 0.2S_{DS})D + 0.5L + Q_{DE}$, where Q_{DE} is the vertical load on the isolator bearing due to the design earthquake.
The typical value of the maximum downward design force, about 500 kips, is used to establish upper-bound vertical load for prototype testing of isolator units.



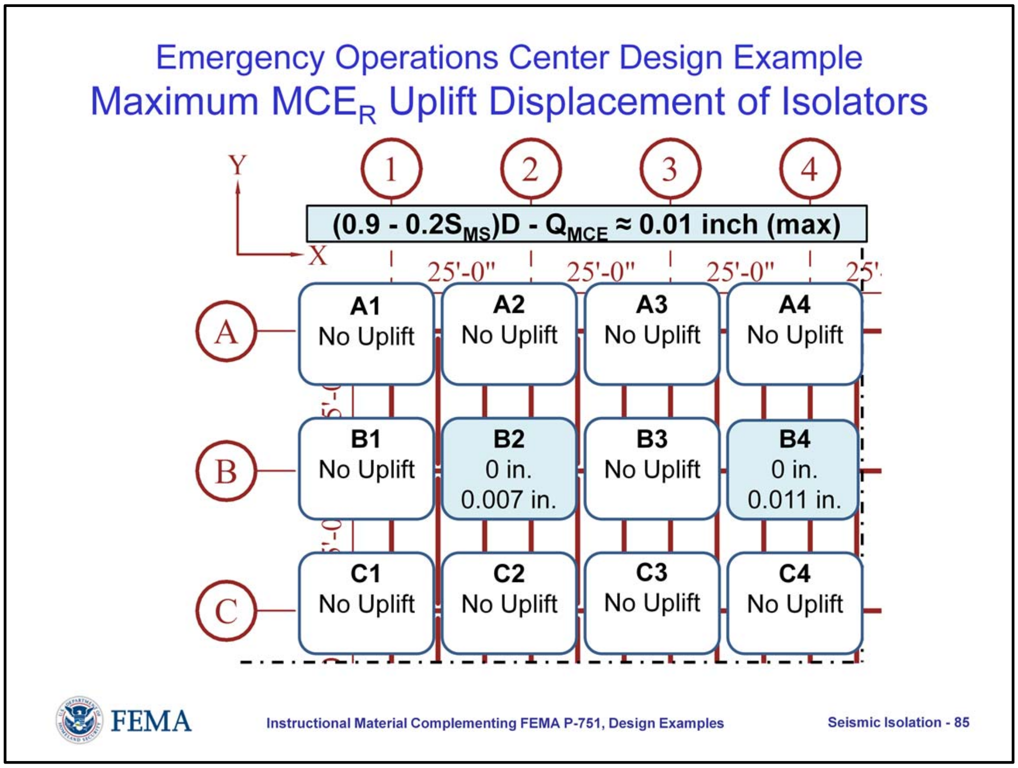
This figure shows minimum downward gravity an earthquake design forces on isolators, based on the load combination, $(0.9D - 0.2S_{DS})D - Q_{DE}$, where Q_{DE} is the vertical load on the isolator bearing due to the design earthquake.

The typical value of the minimum downward design force, about 150 kips, is used to establish lower-bound vertical load for prototype testing of isolator units.



This figure shows maximum downward MCE_R forces on isolators, based on the load combination, $(1.2D + 0.2S_{MS})D + 1.0L + Q_{MCE}$, where Q_{MCE} is the vertical load on the isolator bearing due to the maximum considered earthquake.

The maximum downward design force, about 1,000 kips, is used for prototype testing of isolator units to check stability at maximum MCE_R displacement.



This figure shows maximum MCE_R uplift displacement of isolators, based on the load combination, (0.9D - 0.2S_{MS})D - Q_{MCE}, where Q_{MCE} is the vertical load on the isolator bearing due to the maximum considered earthquake.

The maximum uplift displacement, about 1/100th of an inch, is used for prototype testing of isolator units to check stability at maximum MCE_R displacement (i.e., would a small amount of uplift cause the bearing to malfunction?).

This slide concludes the presentation of preliminary design using ELF methods, the next series of slides addresses dynamic analysis requirements and verification of the design of the example EOC using response history analysis (RHA) methods

Emergency Operations Center Design Example

RHA Final Design (Design Verification)

- Dynamic analysis (RSA or RHA) is required for design of the EOC building since $S_1 \geq 0.60g$ and $T_M > 3.0s$
- RHA is not required for design of the EOC building since site conditions are not "soft" and the isolation system meets the criteria of Section 17.4.1.7, but is used in this example to:
  - Verify lateral ELF forces used for preliminary design of the structure above the isolation system
  - Calculate maximum displacements used for final design of the isolation system (and testing of individual isolator units)
  - Verify maximum forces used for preliminary design of the isolation system and foundations
  - Verify uplift displacements of individual isolator units

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The *Standard* requires dynamic analysis for design of example EOC since the site is potentially located near an active source (based on the value $S_1 \geq 0.6g$) and because the isolated structure has period, $T_M < 3.0$ seconds. These triggers for required use dynamic analysis date to the original development of isolated structure provisions (more than 20 years ago) and reflect concerns about earthquake ground motions, rather than the method of analysis. Today, ground motion data available from the USGS is much more reliable at long periods, and better incorporate near-field affects.

The requirement for dynamic analysis can be satisfied using response spectrum analysis (RSA) when a site-specific ground motion study is also required (i.e., $S_1 \geq 0.6g$). Since RSA models are linear elastic and use essentially the same effective stiffness and damping properties as the ELF procedure, little is gained with RSA other than a better and more convenient calculation of responses in individual elements of the isolated structure.

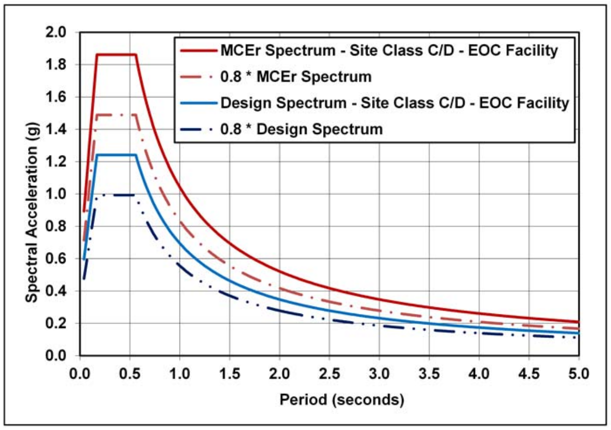
The primary concern for isolated structures located at near-field sites is the potential for ground motions to contain "pulses" that could displace the isolated structure more than predicted by the ELF formulas (or RSA methods). Response history analysis (RHA) using ground motions recorded near fault rupture (and presumably containing "pulses") addresses this concern.

RHA is used in this example to verify ELF design forces (and uplift displacements) and to calculate maximum displacements for design of the isolation system (i.e., to slightly reduce maximum earthquake displacement required for design from that calculated using the ELF procedure).

Emergency Operations Center Design Example

RHA Design Verification – Target Response Spectra

- Target design and MCE_R response spectra of this example use 100 percent of "Code" spectra in lieu of site-specific spectra required for design isolated structures located at sites with $S_1 \geq 0.6$ g (Section 11.4.7)



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In this example, site-specific design earthquake MCE_R spectra were taken as equal to 100 percent of their respective "Code" spectra shown in this figure, rather than calculating actual site-specific spectra in accordance with *Standard* Section 21.1. While this approach would not be permitted for design of real building, use of Code spectra was convenient for the example EOC and also provides for an "apples-to-apples" comparison of RHA results and ELF design parameters.

Emergency Operations Center Design Example
RHA Design Verification - Earthquake Record Selection

- Select earthquake ground motion records to match seismic source and site conditions of the EOC facility
  - Seismic source (dominant fault) information available from site hazard de-aggregation (https://geohazards.usgs.gov/deaggint/2008/)
  - Site conditions may be assumed (e.g., Site Class D) or determined by geotechnical study (i.e., $v_{s,30}$)
- EOC site seismic hazard dominated by the Hayward fault:
  - Fault type - Strike-slip
  - Characteristic magnitude – M7+
  - Fault Proximity – Within 6 km (near source)
- EOC site conditions:
  - Site Class – Site Class C/D ($v_{s,30}$ = 450 meters/sec.)

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Standard Section 17.3.2 defers to Chapter 16 ("Seismic Response history Procedure") for ground motion record selection and scaling requirements, with the exception that selected ground motion records need only envelop the target spectrum (e.g., Code spectrum in this example) at periods from $0.5T_D$ to $1.25T_M$.(i.e., Chapter 16 requires enveloping the target spectrum over a broader range of fixed-base building periods). Most of the selection and scaling requirements of Chapter 16 were initially developed for isolated structures and may be found in the isolation provisions of older editions of seismic codes. Ideally, ground motions are selected from recorded events whose earthquake magnitude, fault type, distance to the plane of fault rupture and site conditions are the same or comparable to those of the site of interest and the fault that governs seismic hazard at the site of interest. The fault that governs seismic hazard at a given site may obtained from a USGS web site that provides hazard de-aggregation data.

For this example, the Hayward fault was found to govern site hazard. The Hayward fault is a strike-slip system that has the capability of producing M7+ events, and is located about 6 km from the assumed location of the example EOC. Site conditions should be determined by a geotechnical study, however, for this example the site conditions were assumed to be Site Class C/D (i.e., shear wave velocity, $v_{s,30}$ = 450 meters/sec.)

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Emergency Operations Center Design Example
Selection of Earthquake Ground Motion Records

- Seven strike-slip records selected from the near-field (NF) and far-field (FF) record sets of FEMA P695 with mean properties:
  - Magnitude = M7.37
  - Distance to source = 5.2 km (JB)
  - Shear wave velocity, $v_{s,30}$ = 446 mps

FEMA P695 Record ID No.	Earthquake			Source Characterisitcs				Site Conditions	
	Year	Name	Record Station	Mag. (M_w)	Distance D_f (km) JB	Distance D_f (km) Rupture	Fault Mechanism	Site Class	$v_{s,30}$ (m/sec.)
NF-8	1992	Landers	Lucerne	7.3	2.2	15.4	Strike-slip	C	685
FF-10	1999	Kocaeli,	Arcelik	7.5	10.6	13.5	Strike-slip	C	523
NF-25	1999	Kocaeli	Yarimca	7.5	1.4	5.3	Strike-slip	D	297
FF-3	1999	Duzce	Bolu	7.1	12.0	12.0	Strike-slip	D	326
NF-14	1999	Duzce	Duzce	7.1	0.0	6.6	Strike-slip	D	276
FF-4	1999	Hector Mine	Hector	7.1	10.4	11.7	Strike-slip	C	685
NF-28	2002	Denali	TAPS PS#10	7.9	0.2	3.8	Strike-slip	D	329
Mean Property of Seven Records				7.37	5.2	9.8			446

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This slide lists the seven earthquake records (two components each) selected for RHA of the example EOC.
The seven records were selected from the 22 Far-Field (FF) records and 28 Near-Field (NF) records of FEMA P-695. FEMA P-695 is a convenient source of the strongest ground motion records recorded to date and available form the PEER NGA database (which has thousand ground motion records, but only a limited number strong ground motion records from large magnitude events recorded relatively close to fault rupture).
The records selected for RHA of example EOC were the seven FEMA P695 records deemed to best match Hayward fault and example EOC site characteristics. As shown in the table, all records are from strike-slip earthquakes whose magnitude is M7.37, on average, whose distance to fault rupture is 5.3 km, on average (using the Joyner-Boore definition of fault distance) and whose site conditions are Site Class C or Site Class D (i.e., $v_{s,30}$ =- 446 meters/sec., on average). It may be noted that the characteristics of these seven records are, on average, essentially the same as those of the example EOC site, and the nearby Hayward fault which governs ground motion hazard at the site.

Emergency Operations Center Design Example
Scaling of Earthquake Ground Motion Records

- Earthquake ground motion records oriented to have a common axis of stronger shaking response (at long periods) and scaled:
  - Average spectrum of SRSS combination of scaled records envelops MCE_R spectrum from 1.75 seconds (0.5 T_D) to 4.9 seconds (1.25 T_M)
  - Average spectrum of the stronger components is comparable to MCE_R spectrum at response periods of interest (e.g., 3.9 seconds for MCE_R analysis)

FEMA P695 Record ID No.	Earthquake			Normalization and Scaling Factors			
	Year	Name	Record Station	PGV_{PEER} (cm/s)	PGV Normal. Factor	Oakland Site	
						DE	MCE
NF-8	1992	Landers	Lucerne	97.2	0.60	0.62	0.94
FF-10	1999	Kocaeli,	Arcelik	27.4	2.13	2.21	3.32
NF-25	1999	Kocaeli	Yarimca	62.4	0.93	0.97	1.46
FF-3	1999	Duzce	Bolu	59.2	0.99	1.02	1.54
NF-14	1999	Duzce	Duzce	69.6	0.84	0.87	1.31
FF-4	1999	Hector Mine	Hector	34.1	1.71	1.78	2.67
NF-28	2002	Denali	TAPS PS#10	98.5	0.59	0.62	0.92
Median Property of Seven Records				58.3	1.00	1.04	1.56

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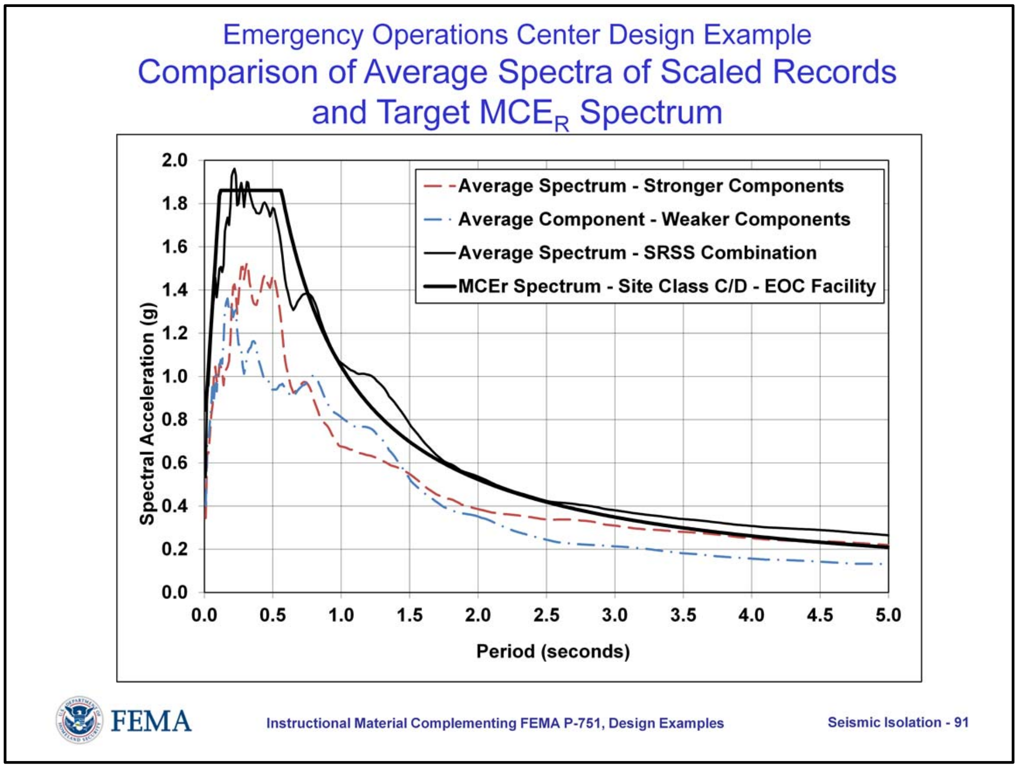
This slide summarizes scaling factors each of the seven records. Chapter 16 of the *Standard* is clear on the objective, but not details of record scaling. For this example, records are first oriented to have a common axis of stronger shaking at long periods of interest. That is, the stronger component of each record is grouped together (e.g., X direction) for subsequent application to the RHA model of example EOC.

Records are scaled by a two step process. First, records are "normalized" in terms of peak ground velocity (PGV). That is, each record is scaled up or down to have the same value of PGV (i.e., 58.3 cm/s). PGV normalization is based on record scaling methods of FEMA P695.

Second, each of the seven records is scaled by the same factor, as required to envelop the target spectrum over the period range of interest. As per the scaling requirements of *Standard* Chapter 16, enveloping criteria require the square-root-sum-of-the-squares (SRSS) combination of the spectra of two horizontal components to equal or exceed the target spectrum (i.e., 100% of the design earthquake spectrum or 100 % of the MCE_R spectrum) at each period of interest.

The table shows the individual and median scale factors for the seven records. It may be noted, that the median scale factor for enveloping the design earthquake (DE) spectrum is 1.04 which implies that the records are, on average, representative of median deterministic ground motions that would be expected at the example EOC site for a large magnitude (M7+) event on Hayward fault.



This figure compares the MCE$_R$ “target” spectrum (heavy black line) with the average spectrum of the SRSS combination of the seven scaled records (solid black line) showing that average spectrum of the SRSS combination (of the two horizontal components) envelops the target spectrum from periods of $0.5T_D$ (1.75 seconds) to 1.25 T_M (4.9 seconds), as required by *Standard* Section 17.3.2. Also shown in this figure, the average spectrum of the seven stronger components and the average spectrum of the seven weaker components (i.e., stronger/weaker at long periods of interest. It may be noted that the average spectrum of the stronger components is approximately equal to the target spectrum at about 4 seconds.

Note. The MCE$_R$ spectrum shown in Figure 12.5-7 of FEMA P751 is not shown correctly (i.e., short-period spectral accelerations should as shown in this slide) – no affect on the design of the example EOC.

Emergency Operations Center Design Example
RHA Design Verification – Modeling

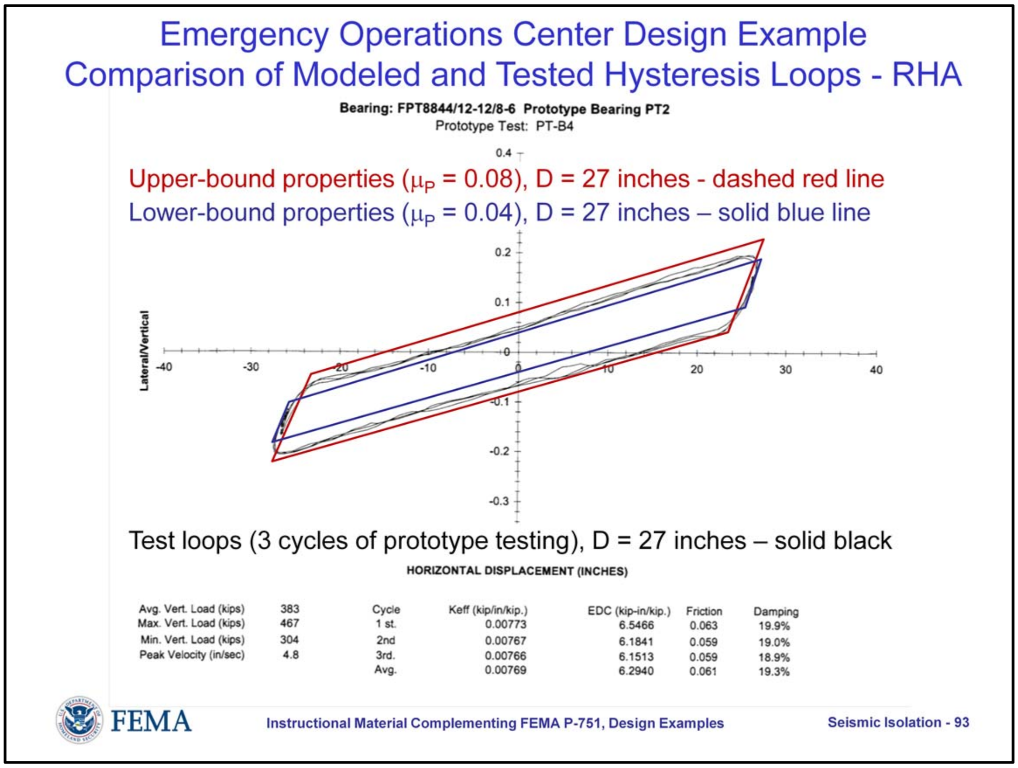
- Isolated Structure Modeling Requirements:
  - Linear elastic model of “essentially elastic” superstructure
  - Explicit nonlinear modeling of isolator units
- Isolation System Modeling Requirements:
  - Properties developed and verified by prototype test (same as ELF)
  - Account for spatial distribution of isolators
  - Consider translation in both horizontal direction (3-dimensional)
  - Access overturning/uplift forces on individual isolator units
  - Account for the effects of vertical load, etc., on isolators
- ETABS Model
  - Same model as that used for pushover (with ELF lateral forces)
  - Isolators modeled as bi-linear elements (representing upper-bound and lower-bound properties of bearing stiffness)

FEMA Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 92

This slide summarizes modeling requirements for RHA as applied to the ETABS model of example EOC structure. The superstructure of an isolated structure is permitted to be modeled as linear elastic provided it remains “essentially elastic.” Such is the case for the example EOC which remained essentially elastic even for MCE_R demands (i.e., since the braces are conservatively sized using ELF forces).

The isolation system of the EOC incorporated two sources of nonlinearity (1) individual isolators were modeled as essentially bi-linear elements using the ETABS “Isolator2” element, and (2) gap elements are used to permit uplift at individual isolators. The ETABS “Isolator2” element was developed to represent bi-linear, hysteretic behavior of FPS bearings and accounts for changes in friction properties with velocity during dynamic response.

Two primary ETABS models were developed representing upper-bound (0.08) and lower-bound (0.04) values of dynamic friction (as illustrated in the next slide).



This figure (copy of Slide 41) shows modeled and tested hysteresis loops for the double-concave FPS bearing at peak displacements of plus/minus 27 inches. The lower-bound and upper-bound loop properties are based on values of dynamic friction of 0.04 and 0.08, respectively, and are intended to bound variation in properties due to aging and environmental effects, manufacturing tolerances, as well test loop variation.

An ETABS model of the isolated structure of the example EOC with bearings modeled with <u>lower-bound</u> bi-linear properties was analyzed using RHA to determine peak isolation system displacements. An ETABS model of the isolated structure of the example EOC with bearings modeled with <u>upper-bound</u> bi-linear properties was analyzed using RHA to determine peak forces in the isolation system and superstructure.

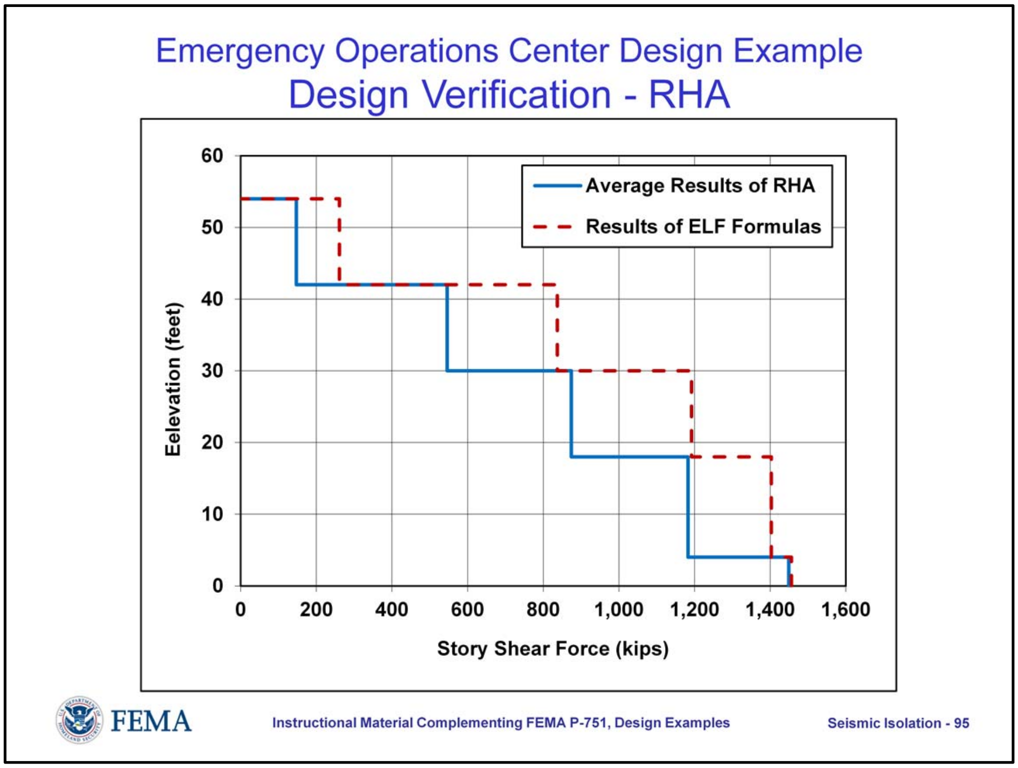
Emergency Operations Center Design Example
Design Verification - RHA

Response Parameter	Method of Analysis		
	ELF Formulas	RHA - Average of Seven Records	
		X-axis Direction	Y-axis Direction
Design Earthquake - Story Shear (kips)			
Penthouse	261	150	147
3rd Story	837	546	531
2nd Story	1,192	874	855
1st Story	1,403	1,183	1173
V_b (Isolators)	1,456	1,440	1449

FEMA Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 94

This slide summarizes the average values of peak story shear force in the X-axis direction and in the Y-axis direction of the isolated structure calculated using RHA and compares these forces with the corresponding value peak story shear force calculated using the ELF procedure. Results shown for RHA results represent the maximum (worst case) of four orientations the larger components of the seven records which were applied to the ETABS model in separate sets of analyses in the (1) positive X-axis direction, (2) negative X-axis direction, (3) positive Y-axis direction and (4) negative Y-axis direction.

As shown in the table, the peak story shear forces in the X-axis direction and Y-axis direction of the isolated are essentially the same (i.e., both governed by the larger components oriented in the direction of interest), and are remarkably similar to the value of shear force at the isolation level. There is, however, a significant difference in the ELF and RHA story shear force results at levels above the isolation interface, as illustrated by the figure in the next slide.



This figure shows that story shear forces calculated using the ELF formula is generally conservative for the example EOC, as compared to the average results of RHA.

This result indicates that higher modes of the isolated structure do not contribute significantly to the response of the upper floors which is, in part, due to the relatively large separation in the period of superstructure (on a fixed base) and the period of the isolated structure. The ratio of isolation system design period (T_D = 3.5 seconds) is over six time the period of the superstructure on a fixed-base.

The results of the RHA verify that forces calculated using the ELF procedure and used for preliminary design are conservative. Preliminary sizes of superstructure elements could be refined (e.g., wall thickness of HSS sections could be reduced), but cost savings would be modest.

Emergency Operations Center Design Example

Design Verification - RHA

Response Parameter	Method of Analysis		
	ELF Formulas	RHA - Average of Seven Records	
		Maximum (X,Y)	X-Y Plane
Design Earthquake - Isolation System Displacement (inches)			
Design (Center)	16.0	15.0	15.9
Total (Corner)	17.6	16.5	17.5
Uplift	NA	No uplift (all records)	
MCE_R - Isolation System Displacement (inches)			
MCE_R (Center)	30.9	28.2	29.6
Total (Corner)	34.0	31.1	32.5
Uplift	NA	Less than 0.01 in. (2/7 records)	

This slide summarizes the average values of peak isolation system displacement calculated using RHA and compare each of these results with the corresponding value calculated using the ELF procedure. Note. Multiple record orientations of the seven records used to determine "worst case" forces, are not required to determine the peak displacement in the horizontal plan (i.e., same for all orientations). However, multiple orientations of records were used to check for potential uplift of individual isolators.

As shown in the table, the peak displacements calculated using ELF formulas and "maximum direction" ground motions compare well with the average displacement in the X-Y plane (maximum direction) calculated by RHA. The slightly smaller values of peak displacement calculated using RHA are used for "final" design of the isolations and for testing of isolator prototypes.

Emergency Operations Center Design Example
Comparison of ELF and RHA Methods – Individual Records

Response Parameter	Seven Scaled Earthquake Ground Motion Records (FEMA P-695 ID No.)							Average Value
	NF-8	FF-10	NF-25	FF-3	NF-14	FF-4	NF-28	
RHA - Peak Isolation System Displacement - Design Earthquake (inches)								
X Direction	14.9	18.3	30.5	7.5	14.2	5.8	13.6	15.0
Y Direction	3.2	4.9	11.3	7.1	9.5	5.6	7.7	7.1
X-Y Direction	15.0	18.8	30.7	8.9	14.9	7.4	15.8	15.9
ELF Estimate of Peak Isolation System Displacement - Design Earthquake (inches) - T_D = 3.5 seconds								
S_{aD} [T_D] (g)	0.182	0.124	0.305	0.106	0.186	0.096	0.133	0.187
S_{dD} [T_D] (in.)	21.9	14.9	36.6	12.7	22.3	11.5	16.0	22.4
$D_D = S_{dM}/B_D$	14.6	9.9	24.4	8.5	14.9	7.7	10.6	15.0
RHA_ Peak Isolation System Displacement - MCE (inches)								
X Direction	28.6	36.5	58.1	11.4	27.3	13.0	22.7	28.2
Y Direction	4.5	9.7	21.8	10.3	18.8	9.0	13.2	12.5
X-Y Direction	28.7	38.1	58.5	13.6	28.6	13.6	26.0	29.6
ELF Estimate of Peak Isolation System Displacement - MCE (inches) - T_M = 3.9 seconds								
S_{aM} [T_M] (g)	0.310	0.295	0.536	0.118	0.225	0.150	0.159	0.256
S_{dM} [T_M] (in.)	46.2	43.9	79.9	17.6	33.6	22.4	23.8	38.2
$D_M = S_{dM}/B_D$	35.5	33.8	61.5	13.5	25.8	17.2	18.3	29.4

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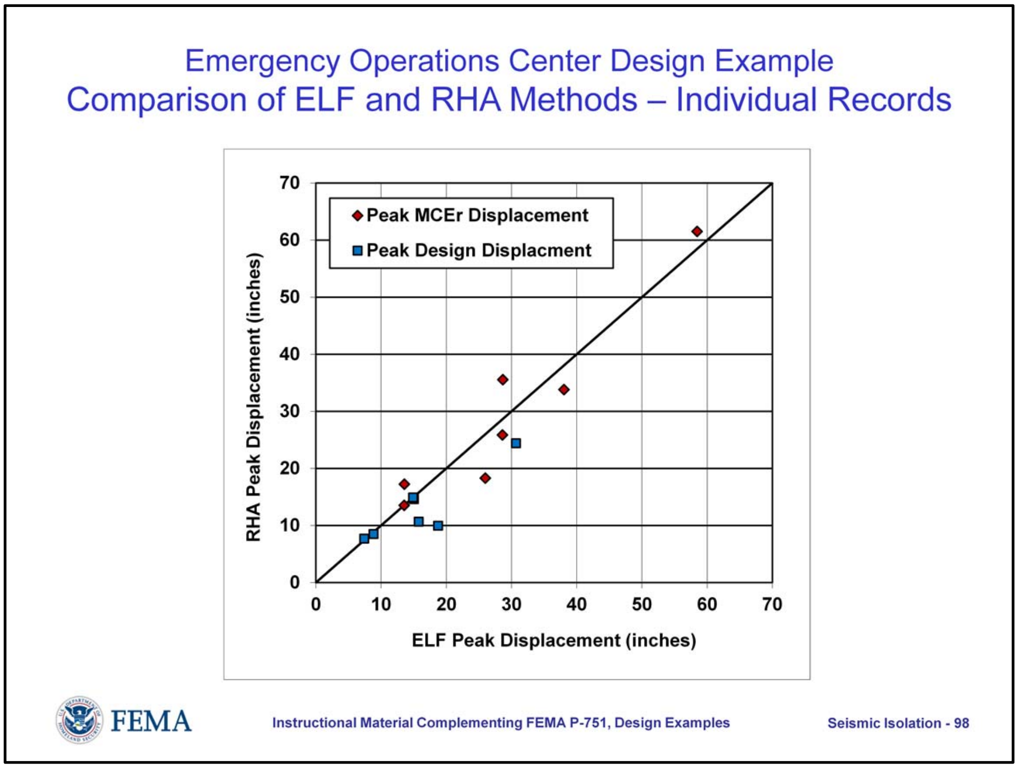
This slide summarizes peak displacement results for each of the seven records as well for the average of the set of seven. RHA results are based on analyses with the larger components oriented in the X-axis direction. Peak displacement results are reported in the X-axis direction, in the Y-axis direction and the in X-Y direction (i.e., maximum displacement in the horizontal plane) for records scaled to the design earthquake spectrum (upper set of brown cells) and for records scaled to MCER spectrum (lower set of brown cells). The *Standard* does not require the isolation system (or the superstructure) to be designed for the worst-case response of the seven records (i.e. just the average response). However, it is important to recognize that there is always the possibility even, if very remote, that design-basis response could be exceeded. In the case of the example EOC, none of the seven records exceed bearing displacement capacity (i.e., 33 inches) for design earthquake ground motions, but two of the seven records (FF-10, NF-25) significantly exceed isolator displacement capacity for MCE_R ground motions. The result of the isolation system trying to respond beyond bearing displacement capacity would be damage to the bearings (and moat wall), higher forces in the superstructure and likely damage to braces (but not structural failure, since the steel SCBFs are designed to yield in a ductile manner).
This slide also summarizes ELF estimates of peak displacement of individual records based on the value of spectral acceleration at the isolated period and the next slide compares these displacements.



This slide compares RHA and ELF displacements from the table of the previous slide. The very close agreement between displacements calculated using RHA and ELF methods (applied to response spectra of individual records) illustrates the usefulness of the ELF procedure, and the related concepts of effective period and effective damping, to provide a "sanity check" on RHA results.

This slide concludes the part of the presentation that has illustrated the example design of a hypothetical seismically-isolated emergency operations center (EOC). The next and final part of the presentation will address required testing of prototype isolator units using material from the EOC design example

Emergency Operations Center Design Example

Prototype Testing – Number and Type of Test Specimens

- Two of Each Isolator Type and Size. Prototype tests shall be performed separately on two full-sized specimens (or sets of specimens, as appropriate) of each predominant type and size of isolator unit of the isolation system
- Wind Restraint System. Test specimens shall include the wind-restraint system as well as individual isolator units is such systems are used in the design
- Prototype Test Specimens Not Permitted for Construction. Test specimens shall not be used for construction unless accepted by the registered design professional
- (Make) Use of Prior Prototype Testing. Prototype testing may be based on prior prototype testing of the same type and size of isolator unit for comparable test loads

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Detailed design of the isolator units typically is the responsibility of the manufacturer subject to design and testing (performance) criteria included in the construction documents (drawings and/or specifications). Performance criteria typically include a basic description and size(s) of isolator units, design criteria (e.g., loads, displacement capacity, force-deflection properties, etc.), quality assurance and quality control requirements (including QC testing of production units) and prototype testing requirements. Section 17.8 of the *Standard* specifies a series prototype tests for establishing and validating design properties. Note. While these test are typically performed on project specific basis, they need only be performed once in comprehensive manner to establish design properties for “standardized” isolator products.
This slide summarizes the number and type of test specimens required for prototype testing.

Emergency Operations Center Design Example

Prototype Testing – Sequence and Cycles

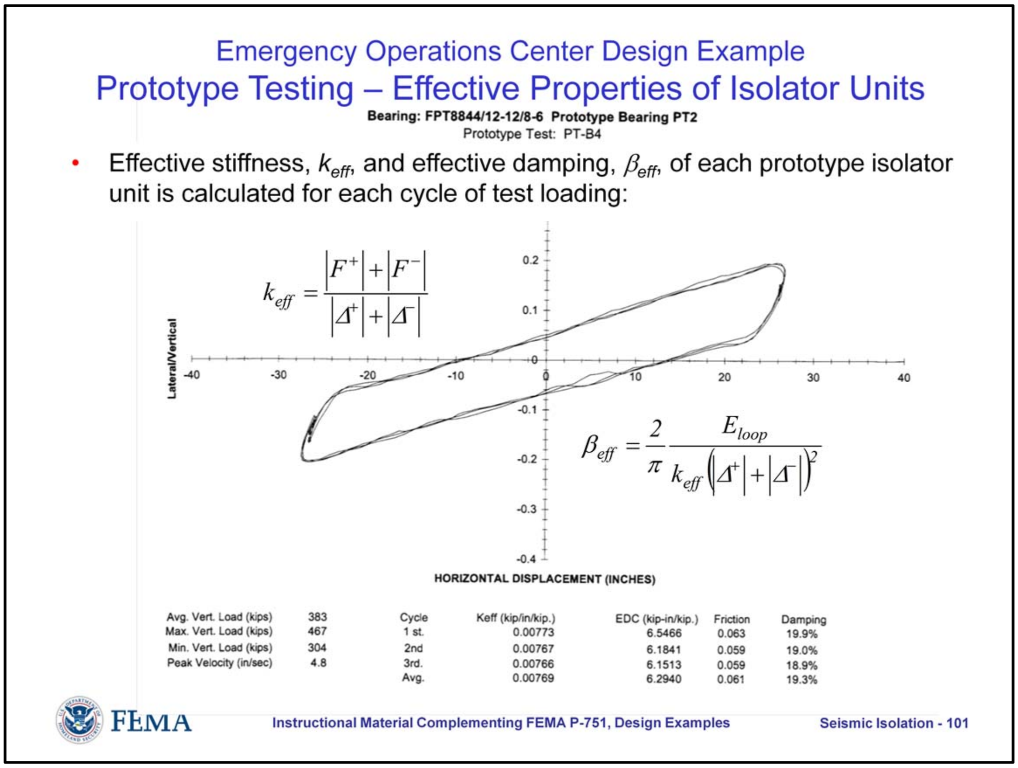
No. of Cycles	*Standard* Criteria		Example EOC Criteria	
	Vertical Load	Lateral Load	Vertical Load	Lateral Load
Cyclic Load Tests to Establish Effective Stiffness and Damping (Standard Sec. 17.8.2.2, w/o Item 1)				
3 cycles	Typical	$0.25D_D$, $0.5D_D$, $1.0D_D$, and $1.0D_M$	290 kips	4, 8, 16 and 30 in.
3 cycles	Upper-bound		500 kips	4, 8, 16 and 30 in.
3 cycles	Lower-bound		150 kips	4, 8, 16 and 30 in.
3 cycles	Typical	$1.0D_{TM}$	290 kips	32.5 in.
Cyclic Load Tests of Durability (Standard Sec. 17.8.2.2)				
$30S_{D1}/S_{DS}B_D$	Typical	1.0D	290 kips	17.5 in.

This slide illustrates the sequence and cycles of prototype testing required by Section 17.8.2.2 of the *Standard* using the design loads and design displacements of the example EOC.

There are three distinct elements of prototype testing. First, cyclic load tests are at incremental displacements are required to establish the force-deflection properties of isolators (e.g., effective stiffness and effective damping) for typical, upper-bound, and lower-bound vertical loads. In the case of the example EOC, incremental test displacements are 4, 8, 16 and 30 inches, and vertical loads are 290 kips (typical vertical load), 150 (lower-bound vertical load) and 500 kips (upper-bound vertical load).

Second, 11 cycles of load at the design displacement (D_{TD}= 17.5 inches) are required to assess isolator prototype "durability" for typical vertical load (290 kips). The number of cycles is based on the formula, 30 $S_{D1}/S_{DS}B_D \geq 10$ cycles of load which is a conservative estimate of the effective number of cycles for two maximum considered earthquake events (i.e., main shock plus after shock as large as the main shock)

Third, a static load test is required to check isolator stability at maximum displacement (D_{TM} = 32.5 inches) for both maximum downward load (1,000 kips) and minimum downward load which includes uplift if the minimum downward load is nil and structure above the bearing moves upward (e.g., 0.1 inch of uplift is specified for example EOC). Note. The test uplift displacement of 0.1 inch (although larger than the 0.01 inch value measured by dynamic (RHA) analysis) is too small to cause bearing malfunction (and could be ignored).



This figure illustrates typical results of cyclic load tests required for determining the force-deflection properties of the isolator. In this illustration, the isolator is loaded with an average vertical load of 383 kips and cycled at low velocities (peak velocity is less than 5 in/sec.) to plus and minus 27 inches of displacement. While the loads of this illustration are not quite the same as those of the example EOC, they are actual test results of the model of double-concave FPS bearing as that used in the design example. Effective stiffness and damping are calculated at each cycle of test, and in this illustration are very similar – the dynamic friction coefficient is about 0.06 and the effective damping is a little over 19% (at 27 inches), on average. As shown on the slide, vertical load varies during cyclic loading (from 304 kips to 467 kips). Cyclic load testing of FPS bearings at large displacements while maintaining a constant vertical load is challenging, since the height of the bearing increases with lateral displacement. Based on the average vertical load, the normalized stiffness is about 0.00769 kip/in./kip which corresponds to force of about 21 percent of the supported weight 27 inches of lateral displacement (i.e., 0.21 ≈ 0.00769 kip/in//kip x 27 inches).

Emergency Operations Center Design Example

Prototype Testing – Maximum and Minimum Effective Properties of the Isolation System at the Design Displacement

Total maximum force at positive D_D (maximum of 3 cycles at a given vertical load level)

$$k_{D\,max} = \frac{\sum \left|F_D^+\right|_{max} + \sum \left|F_D^-\right|_{max}}{2D_D}$$

Maximum effective stiffness
(before modification to account for effects of aging, contamination, etc.)

$$k_{D\,min} = \frac{\sum \left|F_D^+\right|_{min} + \sum \left|F_D^-\right|_{min}}{2D_D}$$

Minimum effective stiffness
(before modification to account for effects of aging, contamination, etc.)

Total loop area at $1.0D_D$ (minimum of 3 cycles at a given load level)

$$\beta_D = \frac{1}{2\pi} \frac{\sum E_D}{k_{D\,max} D_D^2}$$

Effective damping
(before modification to account for effects of aging, contamination, etc.)

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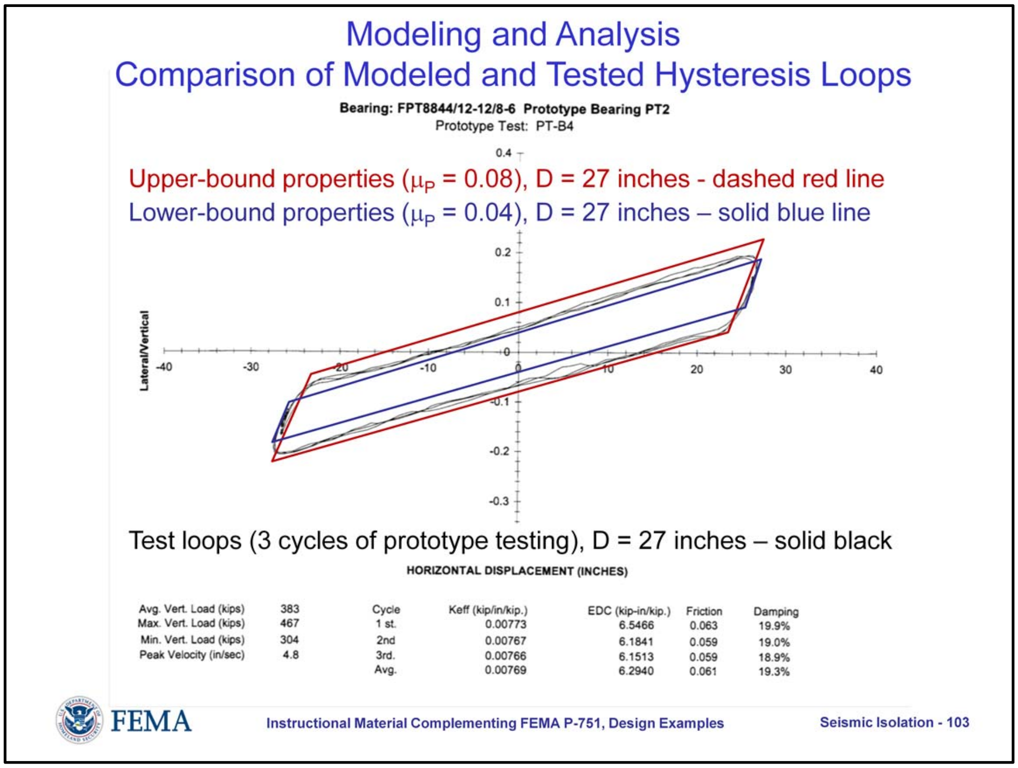
This slide shows formulas for calculating maximum and minimum effective stiffness and effective damping of the isolation system at the design displacement (D). Conceptually, effective stiffness is based on forces at the design displacement, measured by prototype testing, summed over all isolator units, and effective damping is based on the hysteretic loop area at the design displacement, measured by prototype testing, summed over all isolators (and including dampers, if such are used as part of the isolation system). The *Standard* intentional requires conservative values of forces and loop areas (e.g., maximum of 3 cycles at a given load level), although the average value of force or loop area is typically used in practice.

Formulas for maximum and minimum effective stiffness (and effective damping) only address variability of isolator properties measured during prototype testing and should be modified to also include the effects of aging and contamination, etc., and manufacturing tolerances, such that values of maximum and minimum stiffness (and effective damping) used for design reflect the full range of possible isolator properties. Thus, in the design of the example EOC, the value of dynamic friction was assumed to have range from 0.04 to 0.08, although the cyclic load testing showed much less variability around the nominal value of dynamic friction (0.06), as shown in the next slide (repeat of Slide 41).



This figure shows modeled and tested hysteresis loops for the double-concave FPS bearing at peak displacements of plus/minus 27 inches. The lower-bound and upper-bound loop properties are based on values of dynamic friction of 0.04 and 0.08, respectively, and are intentionally conservative with respect to the 0.06 nominal value of dynamic friction to bound potential variation in properties due to aging and environmental effects, manufacturing tolerances as well test loop variation.

Emergency Operations Center Design Example

Prototype Testing – Acceptance Criteria of Test Specimens

- Cyclic-load tests to establish effective stiffness and damping:
  - Force-deflection plots have positive incremental restoring force capacity
  - For each increment of test displacement and vertical load:
    - For each test specimen, the effective stiffness at each of the 3 cycles of test loading is within 15 percent of the average stiffness over the 3 cycles of test load
    - For each of two test specimens (of common type and size), the effective stiffness of one specimen is within 15 percent of the effective stiffness of the other (at each of the 3 cycles of test loading, and on average)
- Cyclic-load tests to check durability – for each test specimen:
  - There is no more than 20 percent change in effective stiffness
  - There is no more than a 20 percent reduction in effective damping
- Static-load tests to verify isolator unit stability
  - All test specimens remain stable (for maximum MCE_R loads)

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The Standard provides acceptance criteria that ensures that isolators, and hence the isolation system:

(1) has positive incremental restoring force capacity – the test specimens should have increasing resistance with displacement to verify that isolation system will not accumulate residual displacement in a given direction

(2) has reliable force-deflection properties – the two test specimens should have the same effective properties and have limited variation in effective stiffness for repeated cycles of load at given displacement

(3) is durable – test specimens should have limited degradation of their effective properties for repeated cycles of load such that the isolation system would still be functional during aftershocks

(4) remains stable for maximum earthquake loads – the tests specimens must be shown capable of supporting maximum (and minimum) vertical load at maximum (MCE_R) earthquake displacement.

Emergency Operations Center Design Example
Prototype Testing of Double-Concave FPS Bearing (FPT8844/12-12/8-6)

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This photograph shows prototype testing of a double-concave FPS bearing (FPT8844/12-12/8-6) in large test machine located at factory of Earthquake Protection Systems (manufacture). Top concave plate is displaced approximately two feet relative to the bottom concave plate. Articulated slider is tilted to accommodate the curvatures of the two concave plates.

Emergency Operations Center Design Example
Post-Test Inspection of Double-Concave FPS Bearing (FPT8844/12-12/8-6)

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This photograph shows the bottom concave plate and articulated slider of the double-concave PFS bearing (FPT8844/12-12/8-6) after prototype testing. The bearing and the articulated slider have been disassembled for inspection of internal surfaces and parts.

Top and bottom concave plates and articulated slider parts are cast iron with materials added to sliding surfaces. The polished surface inside the bottom concave plate is a stainless steel liner. The sliding surfaces of the articulated slider (black surfaces facing up) are made of a proprietary Teflon-like material that bears on the stainless steel liners of the top and bottom concave plates. The core element of the articulated slider is the object in the center of the bottom concave plate.

Questions

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Slide to initiate questions from the participants.

12

Seismically Isolated Structures

Charles A. Kircher, P.E., Ph.D.

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Presentation Objectives

- Present background material and basic concepts of seismic isolation
- Review seismic-code design requirements:
  - Chapter 17 – ASCE Standard ASCE/SEI 7-05, Minimum Design Loads for Buildings and Other Structures (referred to as the *Standard*)
- Illustrate typical application with a design example of seismically isolated structure
  - Hypothetical three-story emergency operation center (EOC) located in a region of high seismicity

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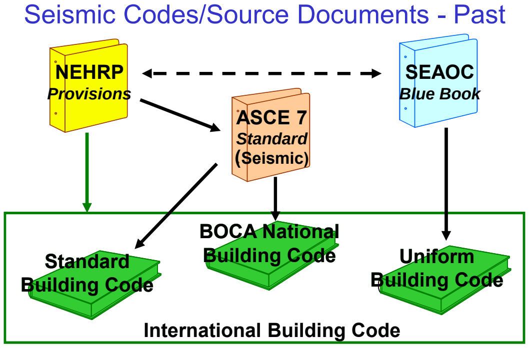
Background and Basic Concepts
Seismic Codes/Source Documents - Past



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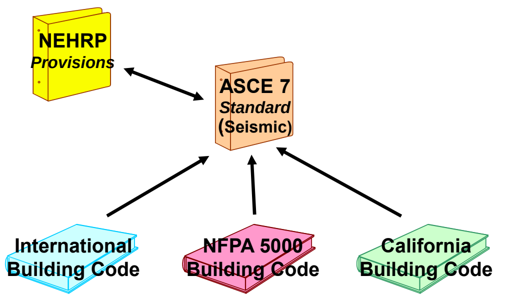
Background and Basic Concepts
Seismic Codes/Source Documents - Current



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Background and Basic Concepts
Earthquake Response Modification

- De-couple structure above the isolation interface from potential damaging earthquake ground motions
- De-couple structure from earthquake ground motions by increasing period of the isolated structure to several times the period of the same structure on a fixed base
  - Trade displacement (of the isolation system) for force (in the structure above the isolation system)

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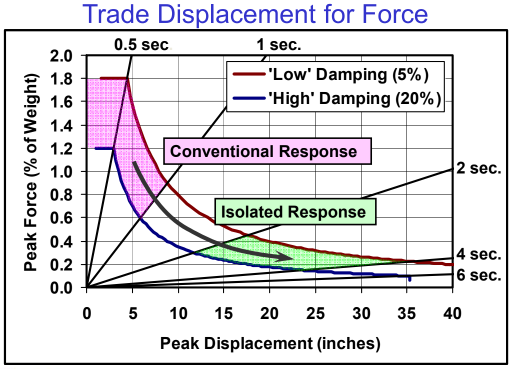
Background and Basic Concepts
Trade Displacement for Force



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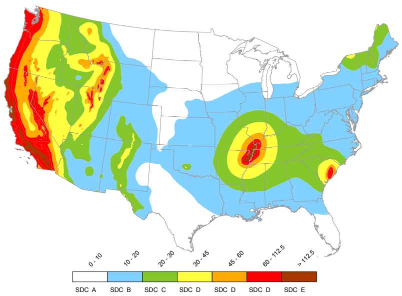
Example – Map of ASCE 7-10 Ground Motions

1-Second MCE_R Spectral Acceleration (Site Class D)



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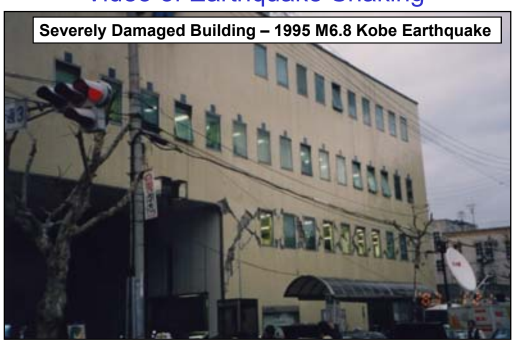
Background and Basic Concepts

Video of Earthquake Shaking



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Background and Basic Concepts

Seismic-Code Performance Objectives

(Section 1.1, 2009 *NEHRP Provisions*)

- Intent of these Provisions is to provide reasonable assurance of seismic performance:
  - Avoid serious injury and life loss
  - Avoid loss of function in critical facilities
  - Minimize nonstructural repair costs (where practical to do so)
- Objectives addressed by:
  - Avoiding structural collapse in very rare, extreme ground shaking
  - Limiting damage to structural and nonstructural systems that could lead to injury, economic loss or loss of functions for smaller more frequent ground motions

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Background and Basic Concepts
Seismic-Code Performance Objectives
(Table C17.2-1 , 2009 *NEHRP Provisions*)

Performance Measure		Earthquake Ground Motion Intensity Level		
Type	Description	Minor	Moderate	Major
Life Safety	Loss of life or serious injury is not expected	F, I	F, I	F, I
Structural Damage	Significant structural damage is not expected	F, I	F, I	I
Nonstructural Damage	Significant nonstructural or contents damage is not expected	F, I	I	I

F indicates fixed-base structures; **I** indicates isolated structures

Background and Basic Concepts
Seismic-Code Performance Objectives
(Implicit for seismically isolated structures)

- Intent of these Provisions is to provide reasonable assurance of seismic performance:
  - Avoid serious injury and life loss
  - Avoid loss of function in ~~critical~~ all facilities
  - Minimize structural, nonstructural and contents repair costs
- Objectives addressed by:
  - Avoiding structural collapse in very rare, extreme ground shaking
  - Avoiding ~~Limiting~~ damage to structural and nonstructural systems and contents that could lead to injury, economic loss or loss of functions for smaller more frequent ground motions by reducing earthquake demands on these systems

Background and Basic Concepts
Seismic Isolation Applications – New Buildings

- Motivating Factors
  - Maintain functionality
  - Protect contents
  - Avoid economic loss
- Typical Applications
  - Hospitals
  - Emergency operations centers
  - Other critical facilities (Risk Category IV)
  - Research facilities (laboratories)
  - Hi-tech manufacturing facilities
  - Art museums

Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

FEMA Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 13

Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Delicate Glass Sculpture - *Nijima and Ikehana* Boats
"Chihuly at the de Young" (2008)

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Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Grade beams and crane Installation

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Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Steel erection – 1st-floor above isolation bearings

Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Steel erection – upper floors

Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Crawl space - rubber bearings on pedestals

Background and Basic Concepts
Example Protection of Contents (and Function)
New de Young Museum – San Francisco

Crawl space – sliding bearing and supplementary fluid viscous damper

Background and Basic Concepts
Isolation System Terminology

- Isolation System

  "The collection of structural elements that includes all individual isolator units, all structural elements that transfer force between elements of the isolation system, and all connections to other structural elements. The isolation system also includes the wind-restraint system, energy-dissipation devices, and/or the displacement restraint system if such systems and devices are used to meet the design requirements of this chapter."

Background and Basic Concepts
Isolation System Terminology

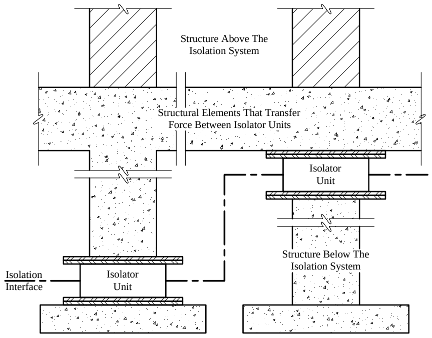
- Isolator Units

  "A horizontally flexible and vertically stiff element of the isolation system that permits large lateral deformations under design seismic load. An isolator unit is permitted to be used either as part of, or in addition to, the weight-supporting system of the structure."

- Isolation Interface

  "The boundary between the upper portion of the structure, which is isolated, and the lower portion of the structure, which moves rigidly with the ground."

Background and Basic Concepts
Isolation System Terminology



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Background and Basic Concepts
Isolation Products Used in the United States

- Elastomeric (rubber) Isolators
  - High-damping rubber (HDR) bearings
  - Lead-rubber (LR) bearings
- Sliding Isolators
  - Friction pendulum system (FPS)
    - Single-concave sliding surface bearings
    - Double-concave sliding surface bearings
    - Triple-pendulum bearings
  - Flat sliding bearings (used with rubber isolators)
- Supplementary Dampers
  - Fluid-viscous dampers

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Background and Basic Concepts
Acceptable Isolation Systems

- The *Standard* permits the use of any type of isolation system or product provided that the system/isolators:
  - Remain stable for maximum earthquake displacements
  - Provide increasing resistance with increasing displacement
  - Have limited degradation under repeated cycles of earthquake load
  - Have well-established and repeatable engineering properties (effective stiffness and damping)
- The *Standard* does not preclude, but does not fully address 3-D isolation systems that isolate the structure in the vertical, as well as the horizontal direction

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Background and Basic Concepts
General Design Requirements – Isolation System

- The *Standard* (Section 17.2.4) prescribes general design requirements for the isolation system regarding:
  - Environmental Conditions
  - Wind Forces
  - Fire Resistance
  - Lateral Restoring Force
  - Displacement Restraint
  - Vertical-load Stability
  - Overturning
  - Inspection and Replacement
  - Quality Control

Background and Basic Concepts
General Design Requirements – Structural System and Nonstructural Components

- The *Standard* (Section 17.2.5) prescribes general design requirements for the structural system regarding:
  - Horizontal Distribution of Force
  - Building Separations
  - Nonbuilding Structures
- The *Standard* (Section 17.2.6) prescribes general design requirements for nonstructural components regarding:
  - Components at or above the Isolation Interface
  - Components Crossing the Isolation Interface
  - Components below the Isolation Interface

Criteria Selection
Acceptable Methods of Analysis*

Site Conditions or Structure Configuration Criteria	ELF Procedure	Response Spectrum	Time History
Site Conditions			
Near-Source ($S_1 \geq 0.6$)	NP	P	P
Soft soil (Site Class E or F)	NP	NP	P
Superstructure Configuration			
Flexible or irregular superstructure (h > 4 stories, h > 65 ft., or $T_M > 3.0$ s, or $T_D \leq 3T$)**	NP	P	P
Nonlinear superstructure (requiring explicit modeling of nonlinear elements, Sec. 17.6.2.2.1)	NP	NP	P
Isolation System Configuration			
Highly nonlinear isolation system or does not	NP	NP	P

* P indicates permitted and NP indicates not permitted by the *Standard*
** T is the elastic, fixed-base, period of the structure above the isolation system

Background and Basic Concepts
Design Approach

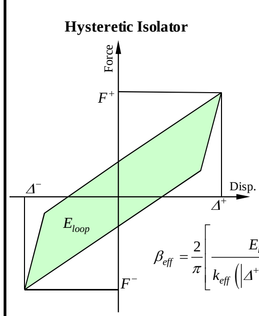
- Design the structure above the isolation system for forces associated with design earthquake ground motions, reduced by only a fraction of the factor permitted for design of conventional, fixed-base buildings (R_I = 3/8R ≤ 2.0)
- Design the isolation system and the structure below the isolation system (e.g., the foundation) for unreduced design earthquake forces (R_I = 1.0)
- Design and prototype test isolator units for forces (including effects of overturning) and displacements associated with the maximum considered earthquake (MCE_R) ground motions
- Provide sufficient separation between the isolated structure and surrounding retaining walls and other fixed obstructions to allow unrestricted movement during MCE_R ground motions

Background and Basic Concepts
Design Approach

- Design the structure above the isolation system, the isolation system, and the structure below the isolation system (e.g., the foundation) for more critical of loads based on bounding values of isolation system force-deflection properties:
  - Design the isolation system for displacements based on minimum effective stiffness of the isolation system
  - Design the structure above for forces based on maximum effective stiffness of the isolation system
- Variations in Material Properties (Section 17.1.1):

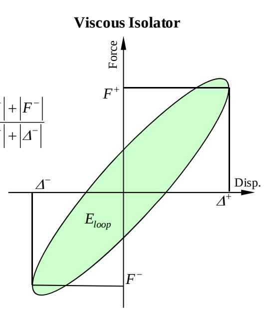
  "The analysis of seismically isolated structures, including the substructure, isolators, and superstructure, shall consider variations in seismic isolator material properties including changes due to aging, contamination, environmental exposure, loading rate, scragging and temperature."

Background and Basic Concepts
Effective Stiffness and Damping

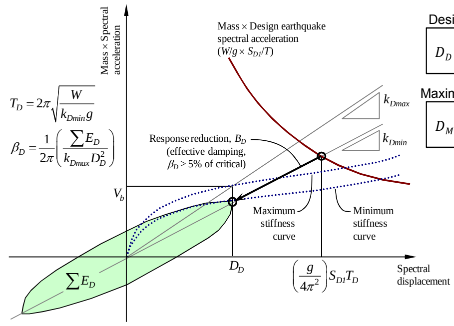


$$k_{eff} = \frac{|F^+| + |F^-|}{|\Delta^+| + |\Delta^-|}$$

$$\beta_{eff} = \frac{2}{\pi}\left[\frac{E_{loop}}{k_{eff}\left(|\Delta^+| + |\Delta^-|\right)^2}\right]$$



Equivalent Lateral Force Procedure
Isolation System Displacement (D_D and D_M)



Design Displacement

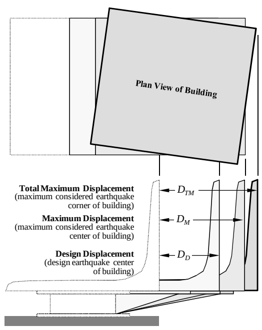
$$D_D = \left(\frac{g}{4\pi^2}\right)\frac{S_{D1}T_D}{B_D}$$

Maximum Displacement

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

B_D, B_M	β_D, β_M
0.8	≤ 2%
1.0	5%
1.2	10%
1.35	15%
1.5	20%
1.7	30%

Equivalent Lateral Force Procedure
Total Maximum Displacement (D_{TD} and D_{TM})



Total Design Displacement

$$D_{TD} = D_D\left[1 + y\frac{12e}{b^2 + d^2}\right]$$

Total Maximum Displacement

$$D_{TM} = D_M\left[1 + y\frac{12e}{b^2 + d^2}\right]$$

Where:

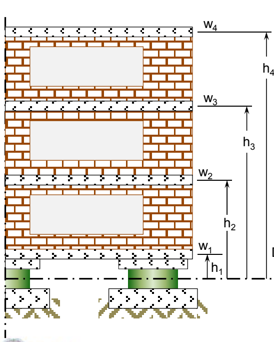
y = distance in plan from center of rigidity to corner

e = actual plus accidental eccentricity (i.e., 0.05d)

b = shortest plan dimension

d = longest plan dimension

Equivalent Lateral Force Procedure
Design Forces (V_b, V_s and F_x)



Design Shear Force at Level x

$$F_x = \frac{V_s w_x h_x}{\sum_i w_i h_i}$$

Design Shear – Isolated Structure

$$V_s = \frac{V_b}{R_I} = \frac{k_{Dmax}D_D}{R_I}$$

V_s must be at least as large as:

(1) Fixed-base design shear force (T = T_D)

(2) Wind design shear force

(3) 1.5 times shear force required to activate the Isolation system

Design Shear – Isolation System/Structure below

$$V_b = k_{Dmax}D_D$$

Isolation Level

Equivalent Lateral Force Procedure
Response Modification Factor (R_I)

- Response modification factor (R_I) required for design of the structure above the isolation system is limited to:

$$R_I = \frac{3}{8}R \;\; \leq 2$$

- Example values of R_I for high-seismic SDC D, E and F structures:

Seismic Force Resisting System	Standard		IBC	
	Fixed Base (R)	Isolated (R_I)	Fixed Base (R)	Isolated (R_I)
Steel Ordinary Concentric Brace Frames	3¼[1]	1.2	3¼[1]	1.0[2]
Steel Special Concentric Braced Frames	6	2	6	2
Steel Ordinary Moment Frames	NP	NP	NP	1.0[2]
Steel Special Moment Frames	8	2	8	2

1. Limited to 35 feet (SDC D and E); NP in SDC F
2. 2006 IBC permits steel OCBFs and steel OMFs designed for R_I = 1.0 and AISC 341

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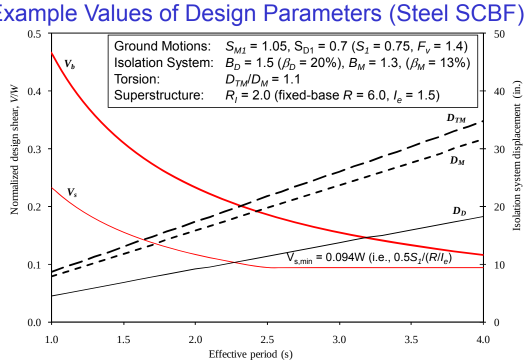
Equivalent Lateral Force Procedure
Example Values of Design Parameters (Steel SCBF)



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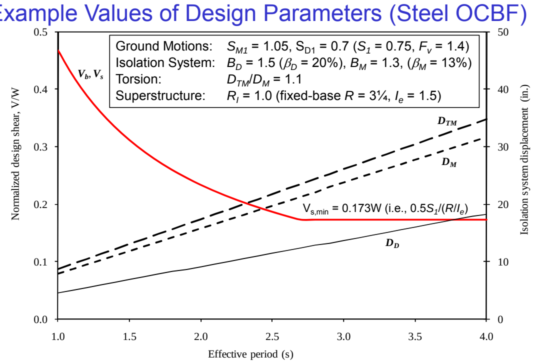
Equivalent Lateral Force Procedure
Example Values of Design Parameters (Steel OCBF)



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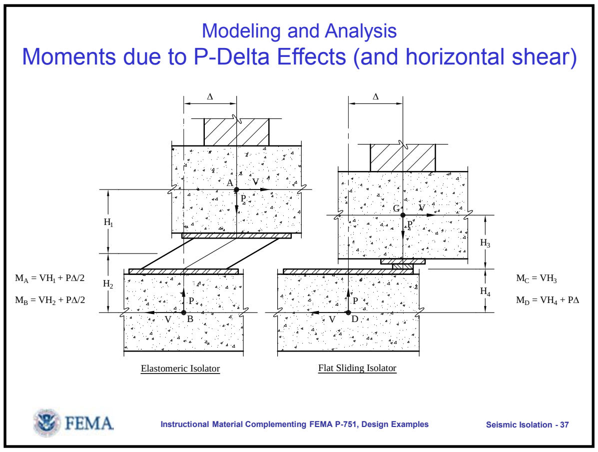
Modeling and Analysis
Moments due to P-Delta Effects (and horizontal shear)
$M_A = VH_1 + P\Delta/2$
$M_B = VH_2 + P\Delta/2$
$M_C = VH_3$
$M_D = VH_4 + P\Delta$
Elastomeric Isolator
Flat Sliding Isolator
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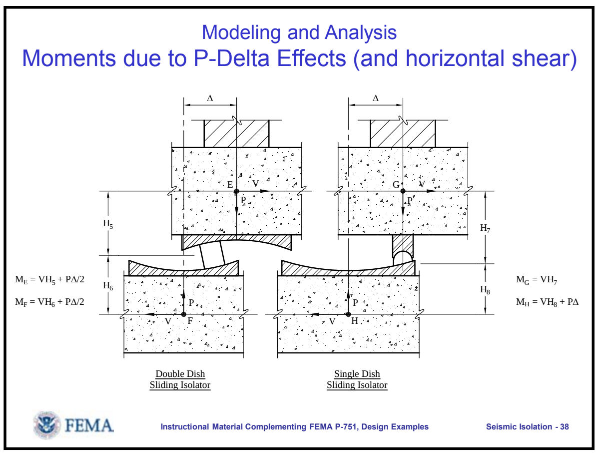
Seismic Isolation - 37


Modeling and Analysis
Moments due to P-Delta Effects (and horizontal shear)
$M_E = VH_5 + P\Delta/2$
$M_F = VH_6 + P\Delta/2$
$M_G = VH_7$
$M_H = VH_8 + P\Delta$
Double Dish Sliding Isolator
Single Dish Sliding Isolator
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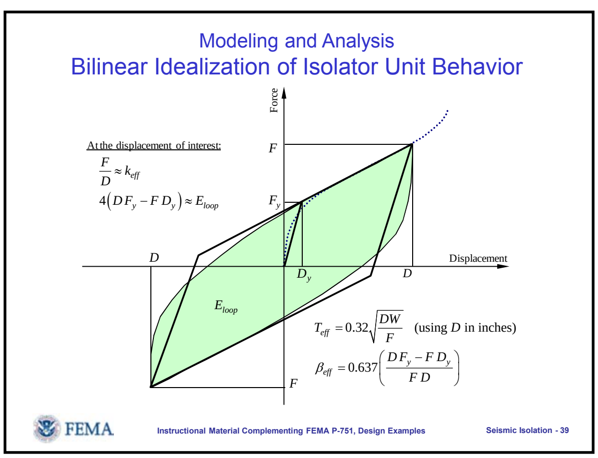
Seismic Isolation - 38


Modeling and Analysis
Bilinear Idealization of Isolator Unit Behavior
At the displacement of interest:
$\frac{F}{D} \approx k_{eff}$
$4(DF_y - FD_y) \approx E_{loop}$
Force
Displacement
E_{loop}
$T_{eff} = 0.32\sqrt{\frac{DW}{F}}$ (using D in inches)
$\beta_{eff} = 0.637\left(\frac{DF_y - FD_y}{FD}\right)$
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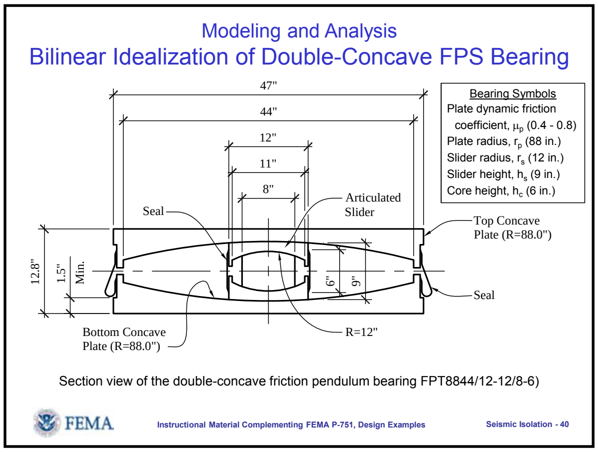
Seismic Isolation - 39


Modeling and Analysis
Bilinear Idealization of Double-Concave FPS Bearing
47"
44"
12"
11"
8"
Bearing Symbols
Plate dynamic friction coefficient, μp (0.4 - 0.8)
Plate radius, rp (88 in.)
Slider radius, rs (12 in.)
Slider height, hs (9 in.)
Core height, hc (6 in.)
Seal
Articulated Slider
Top Concave Plate (R=88.0")
Seal
12.8"
1.5"
Min.
6"
9"
Bottom Concave Plate (R=88.0")
R=12"
Section view of the double-concave friction pendulum bearing FPT8844/12-12/8-6)
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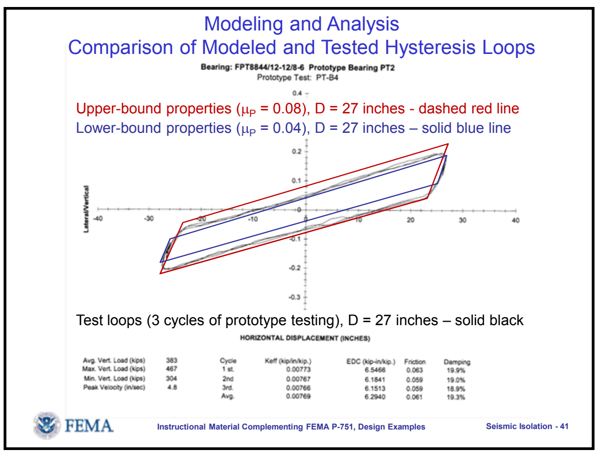
Instructional Material Complementing FEMA P-751, Design Examples
Seismic Isolation - 40


Modeling and Analysis
Comparison of Modeled and Tested Hysteresis Loops
Bearing: FPT8844/12-12/8-6 Prototype Bearing PT2
Prototype Test: PT-B4
Upper-bound properties (μP = 0.08), D = 27 inches - dashed red line
Lower-bound properties (μP = 0.04), D = 27 inches – solid blue line
Lateral/Vertical
Test loops (3 cycles of prototype testing), D = 27 inches – solid black
HORIZONTAL DISPLACEMENT (INCHES)
Avg. Vert. Load (kips) 383
Max. Vert. Load (kips) 467
Min. Vert. Load (kips) 304
Peak Velocity (in/sec) 4.8
Cycle Keff (kip/in/kip.) EDC (kip-in/kip.) Friction Damping
1 st. 0.00773 6.5466 0.063 19.9%
2nd 0.00767 6.1841 0.059 19.0%
3rd. 0.00766 6.1513 0.059 18.9%
Avg. 0.00769 6.2940 0.061 19.3%
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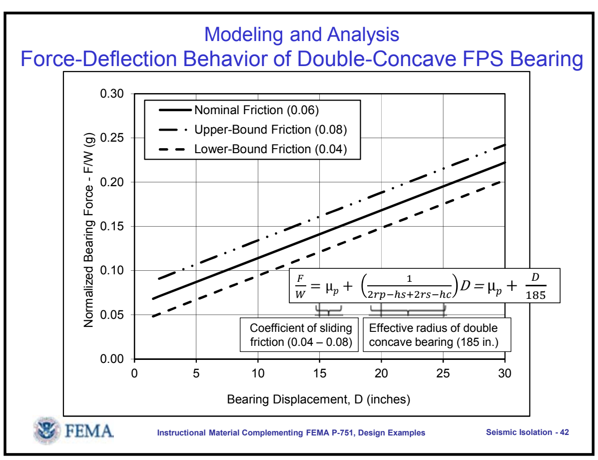
Seismic Isolation - 41


Modeling and Analysis
Force-Deflection Behavior of Double-Concave FPS Bearing
Nominal Friction (0.06)
Upper-Bound Friction (0.08)
Lower-Bound Friction (0.04)
Normalized Bearing Force - F/W (g)
F/W = μp + (1/(2rp−hs+2rs−hc)) D = μp + D/185
Coefficient of sliding friction (0.04 – 0.08)
Effective radius of double concave bearing (185 in.)
Bearing Displacement, D (inches)
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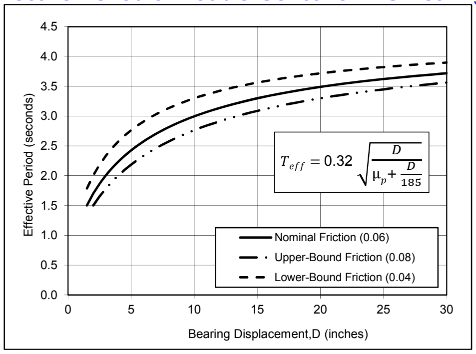
Seismic Isolation - 42

Modeling and Analysis
Effective Period of Double-Concave FPS Bearing



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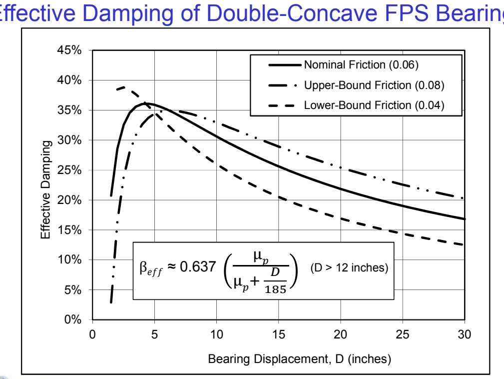
Modeling and Analysis
Effective Damping of Double-Concave FPS Bearing



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Dynamic Lateral Response Procedures
RSA and RHA Procedures

- General – While the equivalent lateral force (ELF) procedure is useful for preliminary design, the *Standard* requires dynamic analysis for most isolated structures (and is commonly used for design even when not required)
- Response Spectrum Analysis (RSA) Procedure – RSA is useful for design of the superstructure which remains essentially elastic for design earthquake ground motions
- Response History Analysis (RHA) Procedure – RHA procedure is useful for verification of maximum isolation system displacement, etc., for MCE_R ground motions

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Dynamic Lateral Response Procedures
Minimum Design Criteria

- The *Standard* encourages the use of dynamic analysis but recognizes that along with the benefits of more complex model methods also comes an increased chance of error – to avoid possible under-design, the Standard establishes lower-bound limits of the results of RSA and RHA as a percentage of the ELF design parameter:

ELF Design Parameter		Percent of ELF	
Description	Symbol	RSA	RHA
Total Design Displacement	D_{TD}	90%	90%
Total Maximum Displacement	D_{TM}	80%	80%
Design Force – Isolation System (and below)	V_b	90%	90%
Design Force - Irregular Superstructure	V_s	100%	80%

Dynamic Lateral Response Procedures
Modeling Requirements

- Configuration - Dynamic analysis models should account for:
  - Spatial distribution of individual isolator units
  - Effects of actual (and accidental) mass eccentricity
  - Overturning forces and uplift of individual isolator units
  - Variability of isolation system properties (i.e., upper-bound and lower-bound values of stiffness and damping)
- Nonlinear Properties of the Isolators – Model should incorporate nonlinear properties of isolators determined from testing of prototype units (e.g., consistent with effective stiffness and effective damping properties of the ELF procedure)
- Nonlinear Properties of the Superstructure – Model should incorporate nonlinear properties of the superstructure, if RSA is used to justify loads less than those permitted for ELF (not typical)

Dynamic Lateral Response Procedures
Response Spectrum Analysis (RSA)

- Amplitude-dependent values of isolator properties:
  - Same effective stiffness and effective damping properties of isolators as those of the ELF procedure (including separate models/analyses of maximum and minimum values of effective stiffness)
- Modal Damping
  - Effective damping of isolated modes limited to 30 percent of critical
  - Higher modes typically assumed to have 2 to 5 percent damping
- 100%-30% Combination of Horizontal Earthquake Effects
  - Q_E = Max ($1.0Q_{EX} + 0.3Q_{EY}$, $0.3Q_{EX} + 1.0Q_{EY}$)
- Story Design Shear Force Limit
  - Design story shear forces are limited to those of the ELF distribution (over height) anchored to the RSA value of design base shear, V_s

Dynamic Lateral Response Procedures
Response History Analysis (RSA)

- Explicit modeling of nonlinear properties:
  - Typical for modeling of Isolator units
  - Not typical for other elements of the structure
- At least 3 earthquake records:
  - Design based on the maximum response of the 3 records
  - Design based on the average response if 7, or more, records
- Earthquake record selection and scaling:
  - Records are selected with site properties (e.g., soil type), site-to-source distances, and source properties (i.e., fault type, magnitude, etc.) consistent with those that dominate seismic hazard at the site of interest
  - Selected records are scaled to match the "target" spectrum of either design earthquake or MCE_R ground motions over the period range of interest (e.g., $0.5T_M$ to $1.25T_M$).

Emergency Operations Center Design Example
Overview

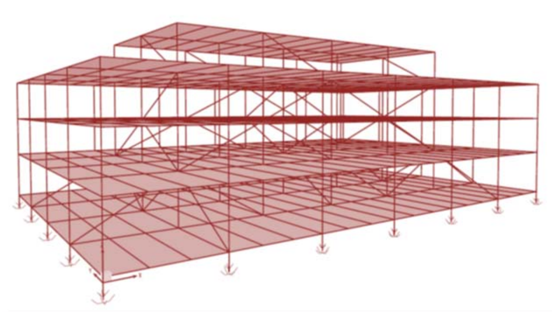
- Design example illustrates the following:
  - Determination of seismic design parameters
  - Preliminary design using ELF procedures
  - Final design (design verification using dynamic analysis)
  - Specification of isolation system testing criteria
- Hypothetical emergency operations center (EOC)
  - Essential Facility - Risk Category IV
  - High Seismic Site – 6 km from an active fault (SDC F)
  - Configuration – approx. 50,000 sf, 3-stories plus mechanical penthouse with helipad
  - Structure - Steel special concentric braced frames
  - Isolators – Double-concave FPS sliding bearings (35 isolators)

Emergency Operations Center Design Example
Structural Design Criteria – Special SCBF

- Height limit (Table 12.2-1, SDC F) — $h < 100$ ft
- Response modification factor (R and R_I):
  - Fixed-base (Table 12.2-1): $R = 6$
  - Isolated (Sec. 17.5.4.2): $R_I = 2$ ($C_d = 2$)
- Importance factor, I_e (Risk Category IV):
  - Fixed-base (Sec. 11.5.1/Table 1.5-2): $I_e = 1.5$
  - Isolated (Sec. 17.2.1): $I_e = 1.0$
- Plan irregularity of superstructure (Table 12.3-1): None
- Vertical irregularity of superstructure (Table 12.3-2): None
- Lateral response procedure (Sec. 17.4.1, $S_1 > 0.6$g): Dynamic Analysis
- Redundancy factor, ρ:
  - Fixed-base (Table 12.3.4): $\rho > 1.0$
  - Isolated (inferred): $\rho = 1.0$

Emergency Operations Center Design Example

3-D ETABS Model of the Structure



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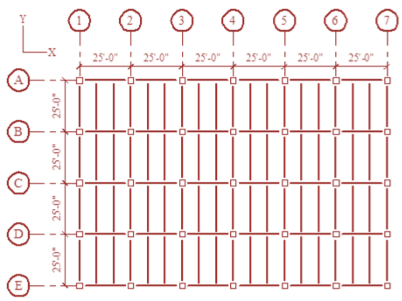
Emergency Operations Center Design Example

Typical Floor Framing Plan



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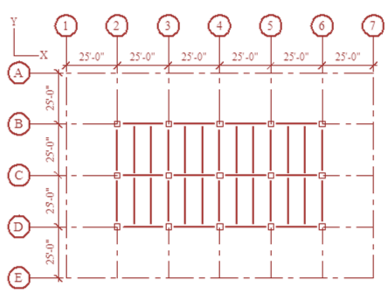
Emergency Operations Center Design Example

Penthouse Roof Framing Plan



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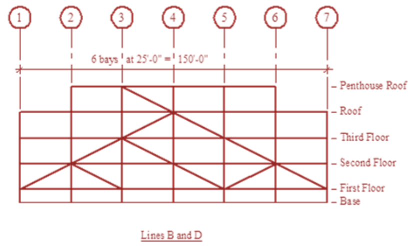
Emergency Operations Center Design Example
Longitudinal Bracing Elevation



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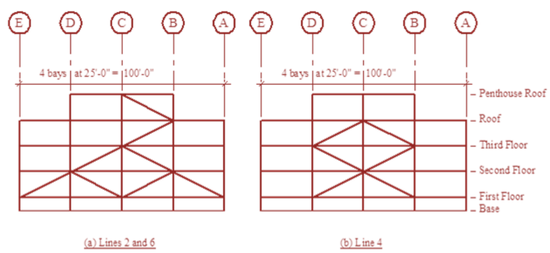
Emergency Operations Center Design Example
Transverse Bracing Elevations



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Emergency Operations Center Design Example
Basic Design Requirements

- Seismic Codes and Standards
  - General: ASCE 7-05 (*Standard*)
  - Seismic: 2009 NEHRP Recommended Provisions
  - Other Loads (load combinations): 2006 IBC
- Materials
  - Concrete: floor slabs $f_c' = 3$ ksi; foundations $f_c' = 5$ ksi; normal weight 150 psf
  - Steel: columns $F_y = 50$ ksi; primary girders (1st-floor) $F_y = 50$ ksi; other girders and beams $F_y = 36$ ksi; braces $F_y = 46$ ksi
  - Steel Deck 3-inch deep, 20-gauge deck

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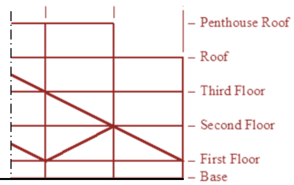
Emergency Operations Center Design Example
Gravity Loads (by elevation)

Elevation	Load	Kips
Penthouse Roof	W_{PR}	794
Roof	W_R	2,251
3rd Floor	W_3	1,947
2nd Floor	W_2	1,922
1st Floor	W_1	2,186
Total Weight	W	9,100
Total Live	L	5,476
Reduced Live	L	2,241

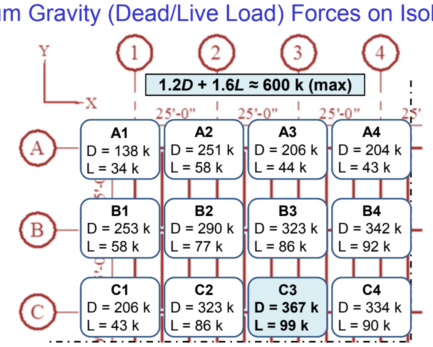


Total dead load (D) weight on isolators

Total unreduced live load

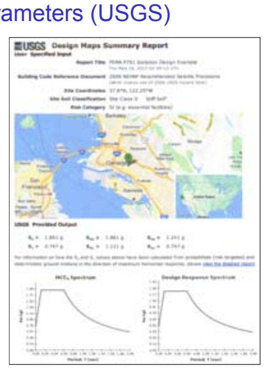
Total reduced live load (L) weight on isolators

Emergency Operations Center Design Example
Maximum Gravity (Dead/Live Load) Forces on Isolators

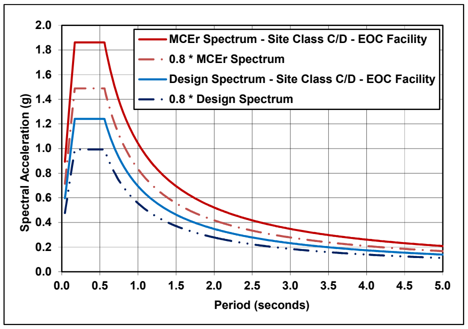


Emergency Operations Center Design Example
Seismic Design Parameters (USGS)

- Design Parameters at USGS website: http://geohazards.usgs.gov/designmaps/
- User enters design data:
  - Code: 2009 NEHRP Provisions
  - Site Classification: Site Class C or D
  - Risk Category: Risk Category IV
  - Site Lat. 37.80° Site Long. - 122.25°
- Summary report provides:
  - Echo print of design data
  - Map showing site location
  - MCE_R and design ground motions:
    - S_{MS} = 1.861 g; S_{DS} = 1.241 g
    - S_{M1} (D) = 1.121 g; S_{D1} = 0.747 g
    - S_{M1} (C) = 0.972 g; S_{D1} = 0.648 g
  - Plots of MCE_R and Design Spectra
  - Supporting Data (long report)



Emergency Operations Center Design Example
Design and MCE_R Response Spectra



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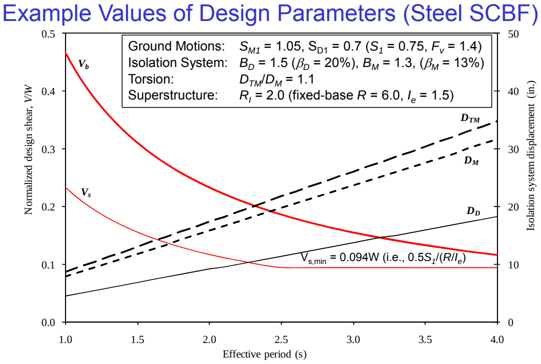
Equivalent Lateral Force Procedure
Example Values of Design Parameters (Steel SCBF)



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Emergency Operations Center Design Example
Preliminary Design – Isolation System

- Isolation system (isolator bearing) selection criteria:
  - Large maximum displacement capacity, $D_{TM} \geq 30$ inches to accommodate very high seismic demands
  - Effective period (design level), $T_D \geq 2.5$ sec., to reduce forces on superstructure and overturning loads on bearings
  - Effective damping (MCE_R level), $\beta_M \geq 10\%$, to limit MCE_R displacement
  - High-damping rubber (HDR) bearings, lead-rubber (LR) bearings and sliding (FPS) bearings are all possible choices
- Double-concave FPS bearing (FPT8844/12-12/8-6) selected:
  - Maximum displacement capacity of about 33 inches
  - Effective period, $T_D \geq 3.5$ sec. at displacement, D > 16 inches
  - Effective damping, $\beta_M \geq 12.5\%$ at displacement, D = 30 inches
  - Load capacity: > 500 kips (long term), > 1,000 kips (short term)

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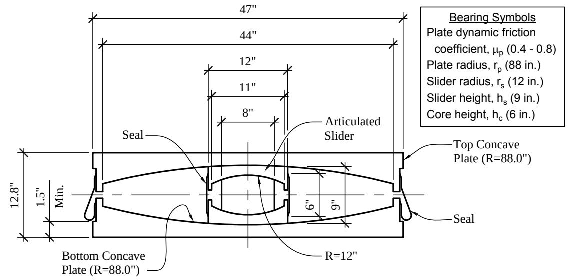
Modeling and Analysis
Double-Concave FPS Bearing



Section view of the double-concave friction pendulum bearing FPT8844/12-12/8-6)

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Emergency Operations Center Design Example
Seismic Force Analysis – ETABS Model

- A linear, 3-D (ETABS) model of the EOC structure was used to expedite calculation of the following loads and load combinations:
  - Gravity loads, including maximum long-term loads on isolators:
    - 1.2D + 1.6L
  - Superstructure design forces for combined gravity and reduced design earthquake load effects ignoring potential uplift of isolators (pushover using ELF lateral forces):
    - $1.2D + 0.5L + E = (1.2 + 0.2S_{DS})D + 0.5L + Q_{DE/2}$
    - $0.9D – E = (0.9 – 0.2S_{DS})D - Q_{DE/2}$
  - Isolation system and foundation design forces for combined gravity and unreduced design earthquake loads and permitting local uplift of individual isolator units (pushover using ELF lateral forces):
    - $1.2D + 0.5L + E = (1.2 + 0.2S_{DS})D + 0.5L + Q_{DE}$
    - $0.9D – E = (0.9 – 0.2S_{DS})D - Q_{DE}$

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Emergency Operations Center Design Example
Seismic Force Analysis – ETABS Model

- A linear, 3-D (ETABS) model of the EOC structure was used to expedite calculation of the following loads and load combinations:
  - Maximum short-term (downward) and minimum short-term (downward) forces on individual isolators for combined gravity and unreduced design earthquake loads (pushover using ELF lateral forces and permitting local uplift of individual isolators)
    - $1.2D + 1.0L + E = (1.2 + 0.2S_{MS})D + 1.0L + Q_{DE}$
    - $0.9D – E = (0.9 – 0.2S_{MS})D - Q_{DE}$
  - Maximum short-term (downward) and minimum short-term (maximum uplift displacement) forces on individual isolators for combined gravity and unreduced MCE_R loads (pushover using ELF lateral forces and permitting local uplift of individual isolators)
    - $1.2D + 1.0L + E = (1.2 + 0.2S_{MS})D + 1.0L + Q_{MCE}$
    - $0.9D – E = (0.9 – 0.2S_{MS})D - Q_{MCE}$

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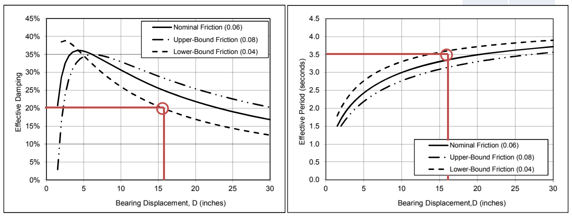
Emergency Operations Center Design Example

Preliminary Design – ELF Displacement

- Design Displacement, D_D:

$$D_D = \left(\frac{g}{4\pi^2}\right)\frac{S_{D1}T_D}{B_D} = (9.8)\frac{0.7(3.5)}{1.5} = 16.0 \text{ in.}$$

B_D, B_M	β_D, β_M
1.2	10%
1.35	15%



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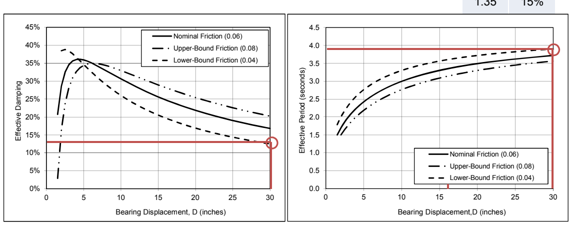
Emergency Operations Center Design Example

Preliminary Design – ELF Displacement

- Maximum Displacement, D_M:

$$D_M = \left(\frac{g}{4\pi^2}\right)\frac{S_{M1}T_M}{B_M} = (9.8)\frac{1.05(3.9)}{1.3} = 30.9 \text{ in.}$$

B_D, B_M	β_D, β_M
1.2	10%
1.35	15%



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Emergency Operations Center Design Example

Preliminary Design – ELF Displacement

- Total Design and Maximum Displacements, D_{TD} and D_{TM}, (e = 0.05d):

$$D_{TD} = DD\left[1 + y\frac{12e}{b^2+d^2}\right] = 16\left[1 + 90\left(\frac{12(0.05)150}{100^2+150^2}\right)\right] = 16\,(1.25)$$

$$D_{TM} = DM\left[1 + y\frac{12e}{b^2+d^2}\right] = 30.9\left[1 + 90\left(\frac{12(0.05)150}{100^2+150^2}\right)\right] = 30.9\,(1.25)$$

- FPS bearings mitigate the effects of mass eccentricity, but additional displacement due to actual plus accidental torsion cannot be taken as less than 1.1 times translation-only displacement which corresponds to e = 0.02d for the geometry of the EOC building:

$$D_{TD} = DD\left[1 + y\frac{12e}{b^2+d^2}\right] = 16\left[1 + 90\left(\frac{12(0.02)150}{100^2+150^2}\right)\right] \geq 16\,(1.1) = 17.6\ in.$$

$$D_{TM} = DM\left[1 + y\frac{12e}{b^2+d^2}\right] = 30.9\left[1 + 90\left(\frac{12(0.02)150}{100^2+150^2}\right)\right] \geq 30.9\,(1.1) = 34\ in.$$

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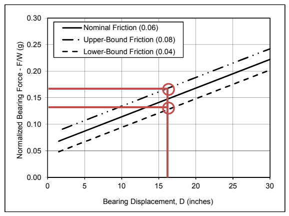
Emergency Operations Center Design Example
Preliminary Design – ELF Effective Stiffness

- Minimum and Maximum Effective Design Stiffness:

$$k_{D\min} = \left(\frac{4\pi^2}{g}\right)\frac{W}{T_D^2} = \left(\frac{1}{9.8}\right)\frac{9,100}{3.5^2} = 75.8 \text{ kips/in.}$$

Maximum effective stiffness is estimated to be about 1.2 times minimum effective displacement at the maximum displacement, D_D = 16 inches

$$k_{D\max} = 1.2(75.8) = 91.0 \text{ kips / in.}$$



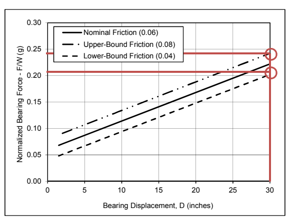
Emergency Operations Center Design Example
Preliminary Design – ELF Effective Stiffness

- Minimum and Maximum Effective MCE_R Stiffness:

$$k_{M\min} = \left(\frac{4\pi^2}{g}\right)\frac{W}{T_D^2} = \left(\frac{1}{9.8}\right)\frac{9,100}{3.9^2} = 61.1 \text{ kips/in.}$$

Maximum effective stiffness is estimated to be about 1.15 times minimum effective displacement at the maximum displacement, D_M = 30.9 inches

$$k_{M\max} = 1.15(61.1) = 70.3 \text{ kips / in.}$$



Emergency Operations Center Design Example
Preliminary Design – ELF Lateral Design Force

- Design of the Isolation System, foundation and structure below:

$V_b = k_{Dmax}\, D_D = 91.0(16.0) = 1{,}456$ kips — 0.16W

- Stability check of Isolation System for MCE_R response:

$V_{MCE} = k_{Mmax}\, D_M = 70.3(30.9) = 2{,}172$ kips — 0.24W

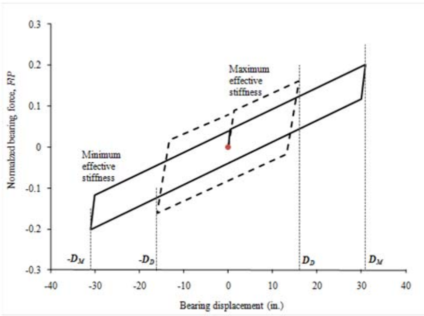
- Design of the structure above the Isolation System:

$V_s = \frac{k_{D\max} D_D}{R_I} = \frac{91.0(16.0)}{2.0} =$ ~~728 kips~~ — ~~0.08W~~

$V_s = 0.5S_1/(R/I_e) = 0.5(0.75)/(6/1.5) =$ ~~853 kips~~ — ~~0.094W~~

$V_s = 1.5\,\mu_{P,\max}\, W = 1.5(0.08)9{,}100 = 1{,}092$ kips — 0.12W

Emergency Operations Center Design Example
Preliminary Design - Hysteresis Loops Used for ELF Design



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Emergency Operations Center Design Example
Preliminary Design – ELF Distribution of Lateral Design Force

Floor level, x (Story)	Floor weight, w_x (kips)	Cumulative weight (kips)	Height above isolation system, h_x (ft)	Story force, F_x, (kips) (Standard Eq. 17.5-9)	Cumulative story force (kips)	Cum. force divided by cumulative weight
PH Roof	794		54			
(Penthouse)		794		196	196	25%
Roof	2,251		42			
(Third)		3,045		432	628	21%
Third Floor	1,947		30			
(Second)		4,992		267	895	18%
Second Flr.	1,922		18			
(First)		6,914		158	1,053	15%

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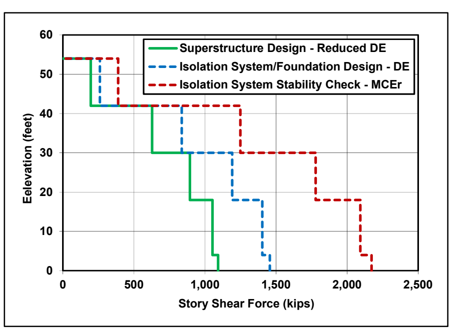
Emergency Operations Center Design Example
Preliminary Design – ELF Distribution of Lateral Design Force



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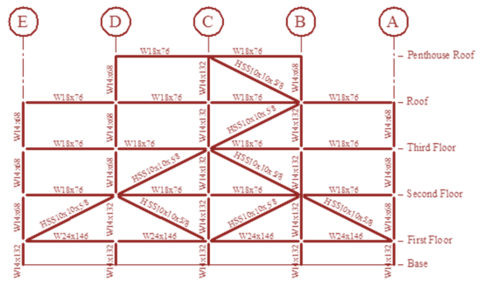
Emergency Operations Center Design Example
Framing on Lines 2 and 6 – Preliminary Design



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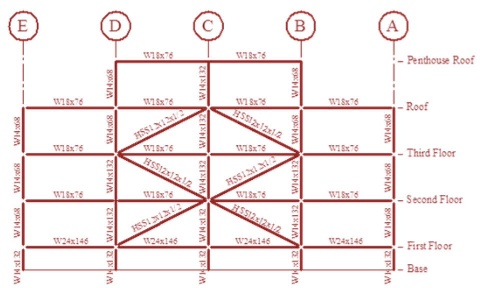
Emergency Operations Center Design Example
Framing on Line 4 – Preliminary Design



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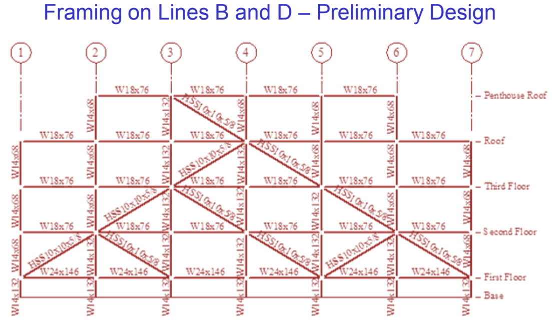
Emergency Operations Center Design Example
Framing on Lines B and D – Preliminary Design



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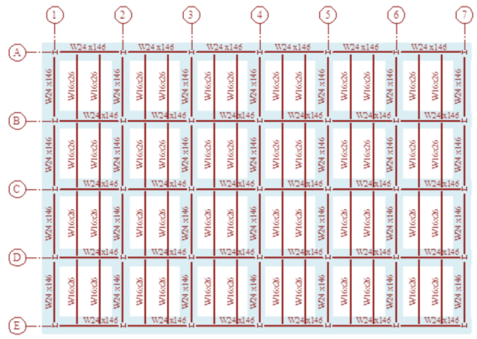
Emergency Operations Center Design Example
First-Floor Framing – Preliminary Design



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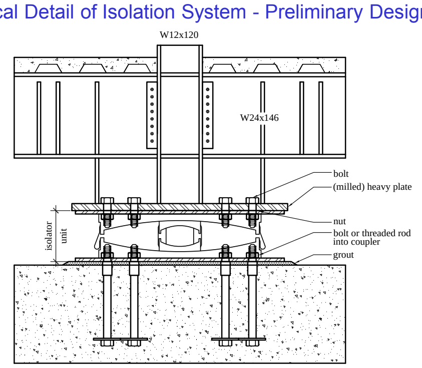
Emergency Operations Center Design Example
Typical Detail of Isolation System - Preliminary Design



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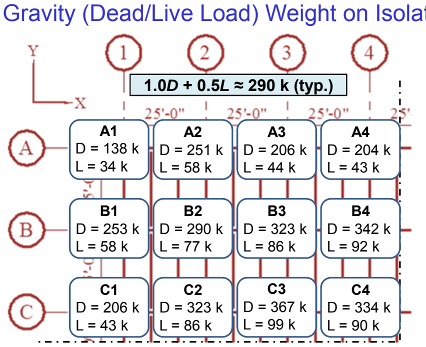
Emergency Operations Center Design Example
Typical Gravity (Dead/Live Load) Weight on Isolators



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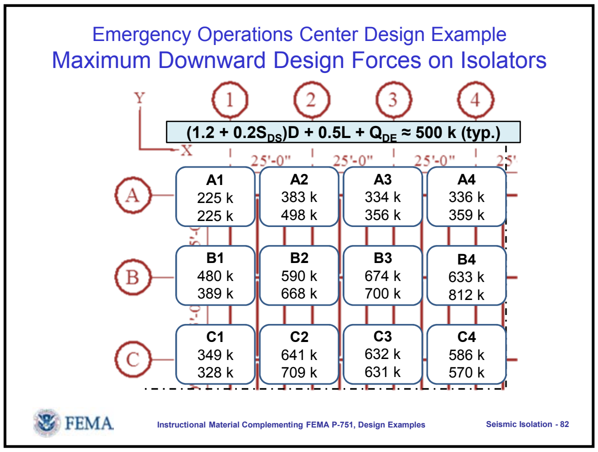
Emergency Operations Center Design Example
Maximum Downward Design Forces on Isolators
(1.2 + 0.2S_DS)D + 0.5L + Q_DE ≈ 500 k (typ.)
Y
X
1
2
3
4
25'-0"
25'-0"
25'-0"
A
B
C
A1 225 k 225 k
A2 383 k 498 k
A3 334 k 356 k
A4 336 k 359 k
B1 480 k 389 k
B2 590 k 668 k
B3 674 k 700 k
B4 633 k 812 k
C1 349 k 328 k
C2 641 k 709 k
C3 632 k 631 k
C4 586 k 570 k
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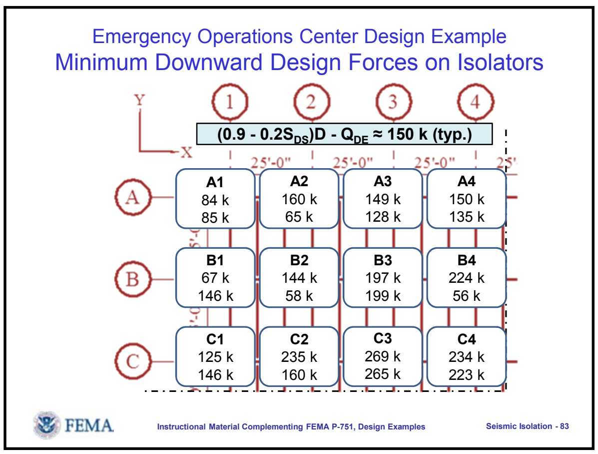
Emergency Operations Center Design Example
Minimum Downward Design Forces on Isolators
(0.9 - 0.2S_DS)D - Q_DE ≈ 150 k (typ.)
Y
X
1
2
3
4
25'-0"
25'-0"
25'-0"
A
B
C
A1 84 k 85 k
A2 160 k 65 k
A3 149 k 128 k
A4 150 k 135 k
B1 67 k 146 k
B2 144 k 58 k
B3 197 k 199 k
B4 224 k 56 k
C1 125 k 146 k
C2 235 k 160 k
C3 269 k 265 k
C4 234 k 223 k
FEMA
Instructional Material Complementing FEMA P-751, Design Examples
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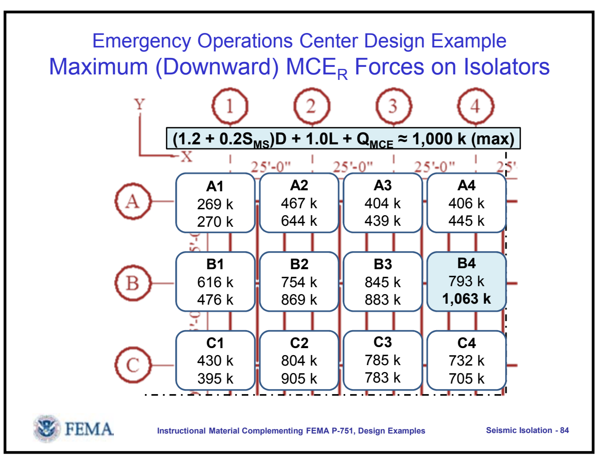
Emergency Operations Center Design Example
Maximum (Downward) MCE_R Forces on Isolators
(1.2 + 0.2S_MS)D + 1.0L + Q_MCE ≈ 1,000 k (max)
Y
X
1
2
3
4
25'-0"
25'-0"
25'-0"
A
B
C
A1 269 k 270 k
A2 467 k 644 k
A3 404 k 439 k
A4 406 k 445 k
B1 616 k 476 k
B2 754 k 869 k
B3 845 k 883 k
B4 793 k 1,063 k
C1 430 k 395 k
C2 804 k 905 k
C3 785 k 783 k
C4 732 k 705 k
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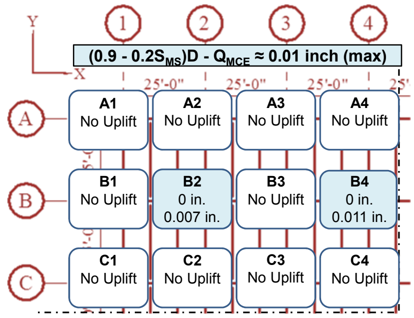
Emergency Operations Center Design Example
Maximum MCE_R Uplift Displacement of Isolators

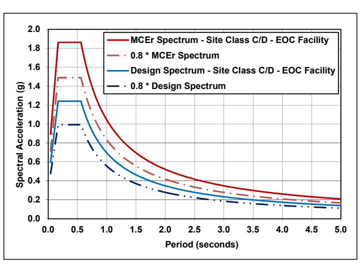


Emergency Operations Center Design Example
RHA Final Design (Design Verification)

- Dynamic analysis (RSA or RHA) is required for design of the EOC building since $S_1 \geq 0.60$g and $T_M > 3.0$s
- RHA is <u>not</u> required for design of the EOC building since site conditions are not “soft” and the isolation system meets the criteria of Section 17.4.1.7, but is used in this example to:
  - Verify lateral ELF forces used for preliminary design of the structure above the isolation system
  - Calculate maximum displacements used for final design of the isolation system (and testing of individual isolator units)
  - Verify maximum forces used for preliminary design of the isolation system and foundations
  - Verify uplift displacements of individual isolator units

Emergency Operations Center Design Example
RHA Design Verification – Target Response Spectra

- Target design and MCE_R response spectra of this example use 100 percent of “Code” spectra in lieu of site-specific spectra required for design isolated structures located at sites with $S_1 \geq 0.6$ g (Section 11.4.7)



Emergency Operations Center Design Example
RHA Design Verification - Earthquake Record Selection

- Select earthquake ground motion records to match seismic source and site conditions of the EOC facility
  - Seismic source (dominant fault) information available from site hazard de-aggregation (https://geohazards.usgs.gov/deaggint/2008/)
  - Site conditions may be assumed (e.g., Site Class D) or determined by geotechnical study (i.e., $v_{s,30}$)
- EOC site seismic hazard dominated by the Hayward fault:
  - Fault type - Strike-slip
  - Characteristic magnitude – M7+
  - Fault Proximity – Within 6 km (near source)
- EOC site conditions:
  - Site Class – Site Class C/D ($v_{s,30}$ = 450 meters/sec.)

Emergency Operations Center Design Example
Selection of Earthquake Ground Motion Records

- Seven strike-slip records selected from the near-field (NF) and far-field (FF) record sets of FEMA P695 with mean properties:
  - Magnitude = M7.37
  - Distance to source = 5.2 km (JB)
  - Shear wave velocity, $v_{s,30}$ = 446 mps

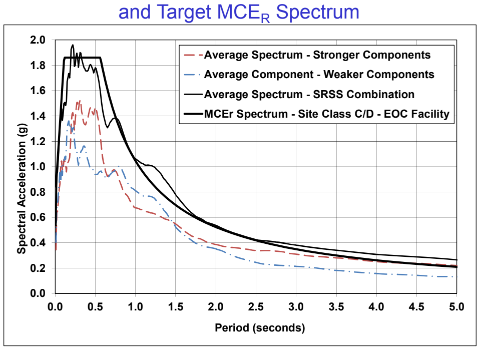
FEMA P695 Record ID No.	Earthquake			Source Characterisitcs				Site Conditions	
	Year	Name	Record Station	Mag. (M_w)	Distance D_r (km) JB	Distance D_r (km) Rupture	Fault Mechanism	Site Class	$v_{s,30}$ (m/sec.)
NF-8	1992	Landers	Lucerne	7.3	2.2	15.4	Strike-slip	C	685
FF-10	1999	Kocaeli,	Arcelik	7.5	10.6	13.5	Strike-slip	C	523
NF-25	1999	Kocaeli	Yarimca	7.5	1.4	5.3	Strike-slip	D	297
FF-3	1999	Duzce	Bolu	7.1	12.0	12.0	Strike-slip	D	326
NF-14	1999	Duzce	Duzce	7.1	0.0	6.6	Strike-slip	D	276
FF-4	1999	Hector Mine	Hector	7.1	10.4	11.7	Strike-slip	C	685
NF-28	2002	Denali	TAPS PS#10	7.9	0.2	3.8	Strike-slip	D	329
Mean Property of Seven Records				7.37	5.2	9.8			446

Emergency Operations Center Design Example
Scaling of Earthquake Ground Motion Records

- Earthquake ground motion records oriented to have a common axis of stronger shaking response (at long periods) and scaled:
  - Average spectrum of SRSS combination of scaled records envelops MCE_R spectrum from 1.75 seconds (0.5 T_D) to 4.9 seconds (1.25 T_M)
  - Average spectrum of the stronger components is comparable to MCE_R spectrum at response periods of interest (e.g., 3.9 seconds for MCE_R analysis)

FEMA P695 Record ID No.	Earthquake			Normalization and Scaling Factors			
	Year	Name	Record Station	PGV_{PEER} (cm/s)	PGV Normal. Factor	Oakland Site DE	Oakland Site MCE
NF-8	1992	Landers	Lucerne	97.2	0.60	0.62	0.94
FF-10	1999	Kocaeli,	Arcelik	27.4	2.13	2.21	3.32
NF-25	1999	Kocaeli	Yarimca	62.4	0.93	0.97	1.46
FF-3	1999	Duzce	Bolu	59.2	0.99	1.02	1.54
NF-14	1999	Duzce	Duzce	69.6	0.84	0.87	1.31
FF-4	1999	Hector Mine	Hector	34.1	1.71	1.78	2.67
NF-28	2002	Denali	TAPS PS#10	98.5	0.59	0.62	0.92
Median Property of Seven Records				58.3	1.00	1.04	1.56

Emergency Operations Center Design Example
Comparison of Average Spectra of Scaled Records and Target MCE_R Spectrum



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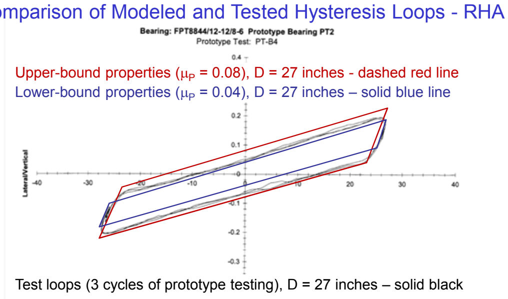
Emergency Operations Center Design Example
RHA Design Verification – Modeling

- Isolated Structure Modeling Requirements:
  - Linear elastic model of "essentially elastic" superstructure
  - Explicit nonlinear modeling of isolator units
- Isolation System Modeling Requirements:
  - Properties developed and verified by prototype test (same as ELF)
  - Account for spatial distribution of isolators
  - Consider translation in both horizontal direction (3-dimensional)
  - Access overturning/uplift forces on individual isolator units
  - Account for the effects of vertical load, etc., on isolators
- ETABS Model
  - Same model as that used for pushover (with ELF lateral forces)
  - Isolators modeled as bi-linear elements (representing upper-bound and lower-bound properties of bearing stiffness)

FEMA Instructional Material Complementing FEMA P-751, Design Examples Seismic Isolation - 92

Emergency Operations Center Design Example
Comparison of Modeled and Tested Hysteresis Loops - RHA



		Cycle	Keff (kip/in/kip.)	EDC (kip-in/kip.)	Friction	Damping
Avg. Vert. Load (kips)	383	1 st.	0.00773	6.5466	0.063	19.9%
Max. Vert. Load (kips)	467	2nd	0.00767	6.1841	0.059	19.0%
Min. Vert. Load (kips)	304	3rd.	0.00766	6.1513	0.059	18.9%
Peak Velocity (in/sec)	4.8	Avg.	0.00769	6.2940	0.061	19.3%

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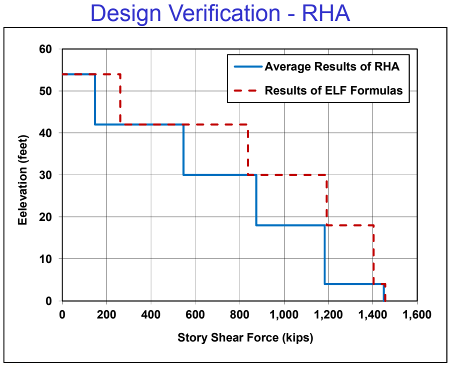
Emergency Operations Center Design Example

Design Verification - RHA

Response Parameter	Method of Analysis		
	ELF Formulas	RHA - Average of Seven Records	
		X-axis Direction	Y-axis Direction
Design Earthquake - Story Shear (kips)			
Penthouse	261	150	147
3rd Story	837	546	531
2nd Story	1,192	874	855
1st Story	1,403	1,183	1173
V_b (Isolators)	1,456	1,440	1449

Emergency Operations Center Design Example

Design Verification - RHA



Emergency Operations Center Design Example

Design Verification - RHA

Response Parameter	Method of Analysis		
	ELF Formulas	RHA - Average of Seven Records	
		Maximum (X,Y)	X-Y Plane
Design Earthquake - Isolation System Displacement (inches)			
Design (Center)	16.0	15.0	15.9
Total (Corner)	17.6	16.5	17.5
Uplift	NA	No uplift (all records)	
MCE_R - Isolation System Displacement (inches)			
MCE_R (Center)	30.9	28.2	29.6
Total (Corner)	34.0	31.1	32.5
Uplift	NA	Less than 0.01 in. (2/7 records)	

Emergency Operations Center Design Example
Comparison of ELF and RHA Methods – Individual Records

Response Parameter	Seven Scaled Earthquake Ground Motion Records (FEMA P-695 ID No.)							Average Value
	NF-8	FF-10	NF-25	FF-3	NF-14	FF-4	NF-28	
RHA - Peak Isolation System Displacement - Design Earthquake (inches)								
X Direction	14.9	18.3	30.5	7.5	14.2	5.8	13.6	15.0
Y Direction	3.2	4.9	11.3	7.1	9.5	5.6	7.7	7.1
X-Y Direction	15.0	18.8	30.7	8.9	14.9	7.4	15.8	15.9
ELF Estimate of Peak Isolation System Displacement - Design Earthquake (inches) - T_D = 3.5 seconds								
S_{aD} [T_D] (g)	0.182	0.124	0.305	0.106	0.186	0.096	0.133	0.187
S_{dD} [T_D] (in.)	21.9	14.9	36.6	12.7	22.3	11.5	16.0	22.4
$D_D = S_{dM}/B_D$	14.6	9.9	24.4	8.5	14.9	7.7	10.6	15.0
RHA_ Peak Isolation System Displacement - MCE (inches)								
X Direction	28.6	36.5	58.1	11.4	27.3	13.0	22.7	28.2
Y Direction	4.5	9.7	21.8	10.3	18.8	9.0	13.2	12.5
X-Y Direction	28.7	38.1	58.5	13.6	28.6	13.6	26.0	29.6
ELF Estimate of Peak Isolation System Displacement - MCE (inches) - T_M = 3.9 seconds								
S_{aM} [T_M] (g)	0.310	0.295	0.536	0.118	0.225	0.150	0.159	0.256
S_{dM} [T_M] (in.)	46.2	43.9	79.9	17.6	33.6	22.4	23.8	38.2
$D_M = S_{dM}/B_D$	35.5	33.8	61.5	13.5	25.8	17.2	18.3	29.4

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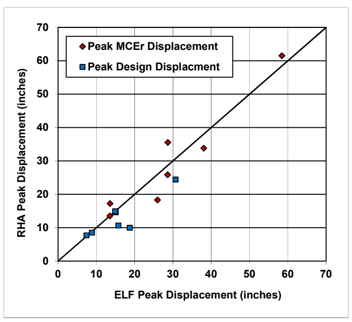
Emergency Operations Center Design Example
Comparison of ELF and RHA Methods – Individual Records



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Emergency Operations Center Design Example
Prototype Testing – Number and Type of Test Specimens

- Two of Each Isolator Type and Size. Prototype tests shall be performed separately on two full-sized specimens (or sets of specimens, as appropriate) of each predominant type and size of isolator unit of the isolation system
- Wind Restraint System. Test specimens shall include the wind-restraint system as well as individual isolator units is such systems are used in the design
- Prototype Test Specimens Not Permitted for Construction. Test specimens shall not be used for construction unless accepted by the registered design professional
- (Make) Use of Prior Prototype Testing. Prototype testing may be based on prior prototype testing of the same type and size of isolator unit for comparable test loads

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Emergency Operations Center Design Example

Prototype Testing – Sequence and Cycles

No. of Cycles	*Standard* Criteria		Example EOC Criteria	
	Vertical Load	Lateral Load	Vertical Load	Lateral Load
Cyclic Load Tests to Establish Effective Stiffness and Damping (Standard Sec. 17.8.2.2, w/o Item 1)				
3 cycles	Typical	$0.25D_D$, $0.5D_D$, $1.0D_D$, and $1.0D_M$	290 kips	4, 8, 16 and 30 in.
3 cycles	Upper-bound		500 kips	4, 8, 16 and 30 in.
3 cycles	Lower-bound		150 kips	4, 8, 16 and 30 in.
3 cycles	Typical	$1.0D_{TM}$	290 kips	32.5 in.
Cyclic Load Tests of Durability (Standard Sec. 17.8.2.2)				
$30S_{D1}/S_{DS}B_D$	Typical	1.0D	290 kips	17.5 in.

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Emergency Operations Center Design Example

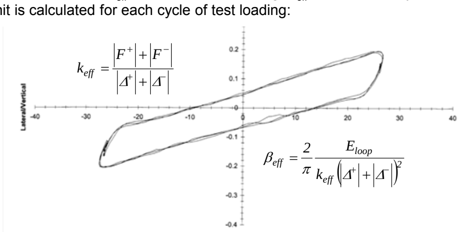
Prototype Testing – Effective Properties of Isolator Units

Bearing: FPT8844/12-12/8-6 Prototype Bearing PT2

Prototype Test: PT-B4

- Effective stiffness, k_{eff}, and effective damping, β_{eff}, of each prototype isolator unit is calculated for each cycle of test loading:

$$k_{eff} = \frac{|F^+| + |F^-|}{|\Delta^+| + |\Delta^-|}$$



$$\beta_{eff} = \frac{2}{\pi} \frac{E_{loop}}{k_{eff}\left(|\Delta^+| + |\Delta^-|\right)^2}$$

		Cycle	Keff (kip/in/kip.)	EDC (kip-in/kip.)	Friction	Damping
Avg. Vert. Load (kips)	383	1 st.	0.00773	6.5466	0.063	19.9%
Max. Vert. Load (kips)	467	2nd	0.00767	6.1841	0.059	19.0%
Min. Vert. Load (kips)	304	3rd.	0.00766	6.1513	0.059	18.9%
Peak Velocity (in/sec)	4.8	Avg.	0.00769	6.2940	0.061	19.3%

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Emergency Operations Center Design Example

Prototype Testing – Maximum and Minimum Effective Properties of the Isolation System at the Design Displacement

Total maximum force at positive D_D (maximum of 3 cycles at a given vertical load level)

$$k_{D\,max} = \frac{\sum |F_D^+|_{max} + \sum |F_D^-|_{max}}{2D_D}$$

Maximum effective stiffness
(before modification to account for effects of aging, contamination, etc.)

$$k_{D\,min} = \frac{\sum |F_D^+|_{min} + \sum |F_D^-|_{min}}{2D_D}$$

Minimum effective stiffness
(before modification to account for effects of aging, contamination, etc.)

Total loop area at $1.0D_D$ (minimum of 3 cycles at a given load level)

$$\beta_D = \frac{1}{2\pi} \frac{\sum E_D}{k_{D\,max} D_D^2}$$

Effective damping
(before modification to account for effects of aging, contamination, etc.)

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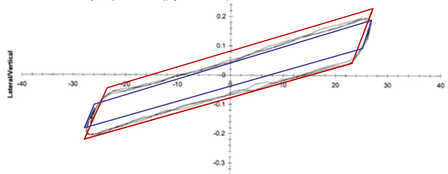
Modeling and Analysis
Comparison of Modeled and Tested Hysteresis Loops

Bearing: FPT8844/12-12/8-6 Prototype Bearing PT2
Prototype Test: PT-B4

Upper-bound properties (μ_P = 0.08), D = 27 inches - dashed red line
Lower-bound properties (μ_P = 0.04), D = 27 inches – solid blue line



Test loops (3 cycles of prototype testing), D = 27 inches – solid black

HORIZONTAL DISPLACEMENT (INCHES)

		Cycle	Keff (kip/in/kip.)	EDC (kip-in/kip.)	Friction	Damping
Avg. Vert. Load (kips)	383					
Max. Vert. Load (kips)	467	1 st.	0.00773	6.5466	0.063	19.9%
Min. Vert. Load (kips)	304	2nd	0.00767	6.1841	0.059	19.0%
Peak Velocity (in/sec)	4.8	3rd.	0.00766	6.1513	0.059	18.9%
		Avg.	0.00769	6.2940	0.061	19.3%

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Emergency Operations Center Design Example
Prototype Testing – Acceptance Criteria of Test Specimens

- Cyclic-load tests to establish effective stiffness and damping:
  - Force-deflection plots have positive incremental restoring force capacity
  - For each increment of test displacement and vertical load:
    - For each test specimen, the effective stiffness at each of the 3 cycles of test loading is within 15 percent of the average stiffness over the 3 cycles of test load
    - For each of two test specimens (of common type and size), the effective stiffness of one specimen is within 15 percent of the effective stiffness of the other (at each of the 3 cycles of test loading, and on average)
- Cyclic-load tests to check durability – for each test specimen:
  - There is no more than 20 percent change in effective stiffness
  - There is no more than a 20 percent reduction in effective damping
- Static-load tests to verify isolator unit stability
  - All test specimens remain stable (for maximum MCE_R loads)

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Emergency Operations Center Design Example
Prototype Testing of Double-Concave FPS Bearing (FPT8844/12-12/8-6)

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Emergency Operations Center Design Example
Post-Test Inspection of Double-Concave FPS Bearing (FPT8844/12-12/8-6)

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Questions

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