SEISMIC PROTECTIVE SYSTEMS: SEISMIC ISOLATION

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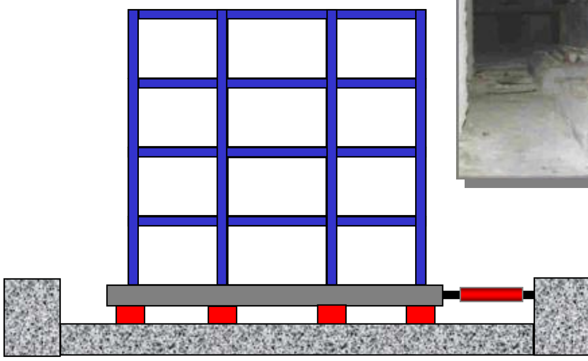

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This presentation describes seismic isolation systems, an innovative approach to protecting structures from seismic hazards. These visuals were presented for the first time at the 2003 MBDSI and updated for the cancelled 2004 MBDSI.

Major Objectives

- Illustrate why use of seismic isolation systems may be beneficial
- Provide overview of types of seismic isolation systems available
- Describe behavior, modeling, and analysis of structures with seismic isolation systems
- Review building code requirements

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Outline

Seismic Base Isolation

- Configuration and Qualitative Behavior of Isolated Building
- Objectives of Seismic Isolation Systems
- Effects of Base Isolation on Seismic Response
- Implications of Soil Conditions
- Applicability and Example Applications of Isolation Systems
- Description and Mathematical Modeling of Seismic Isolation Bearings
  - Elastomeric Bearings
  - Sliding Bearings
- Modeling of Seismic Isolation Bearings in Computer Software
- Code Provisions for Base Isolation

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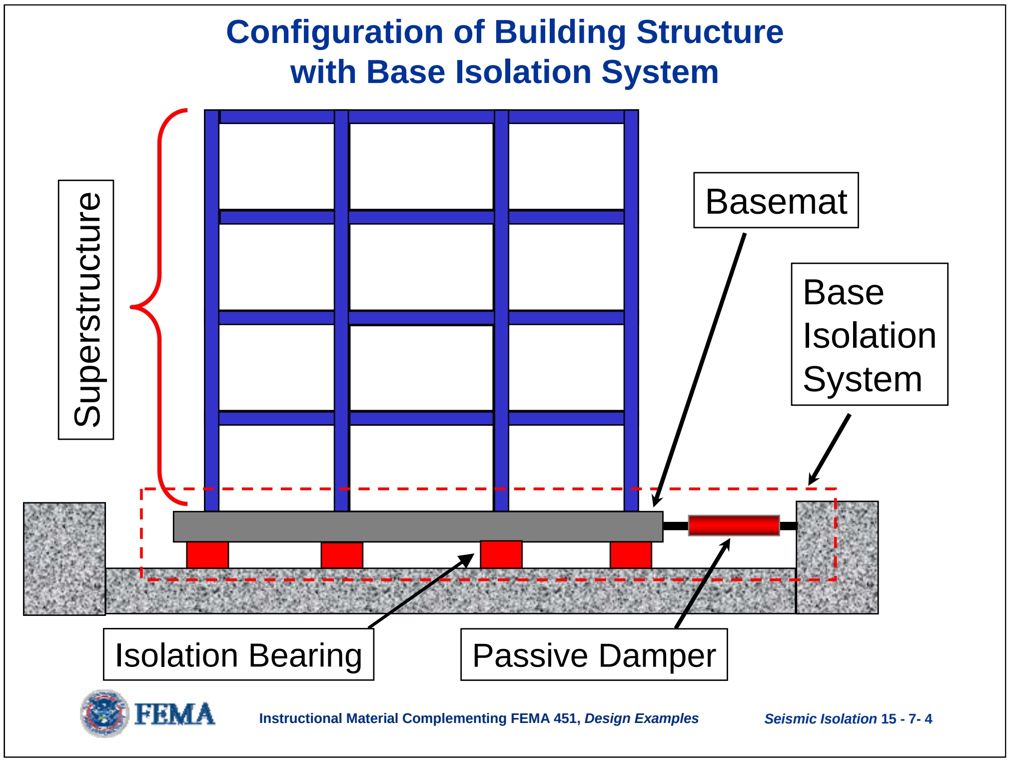
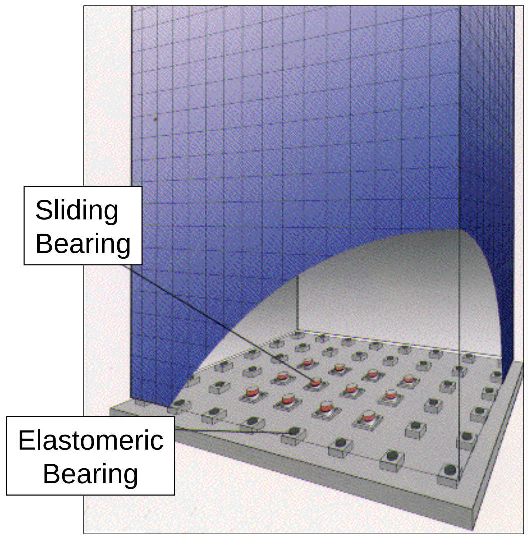


The basic elements of a base isolation system are shown in this slide. Supplemental dampers may or may not be utilized within an isolation system.

Three-Dimensional View of Building Structure with Base Isolation System



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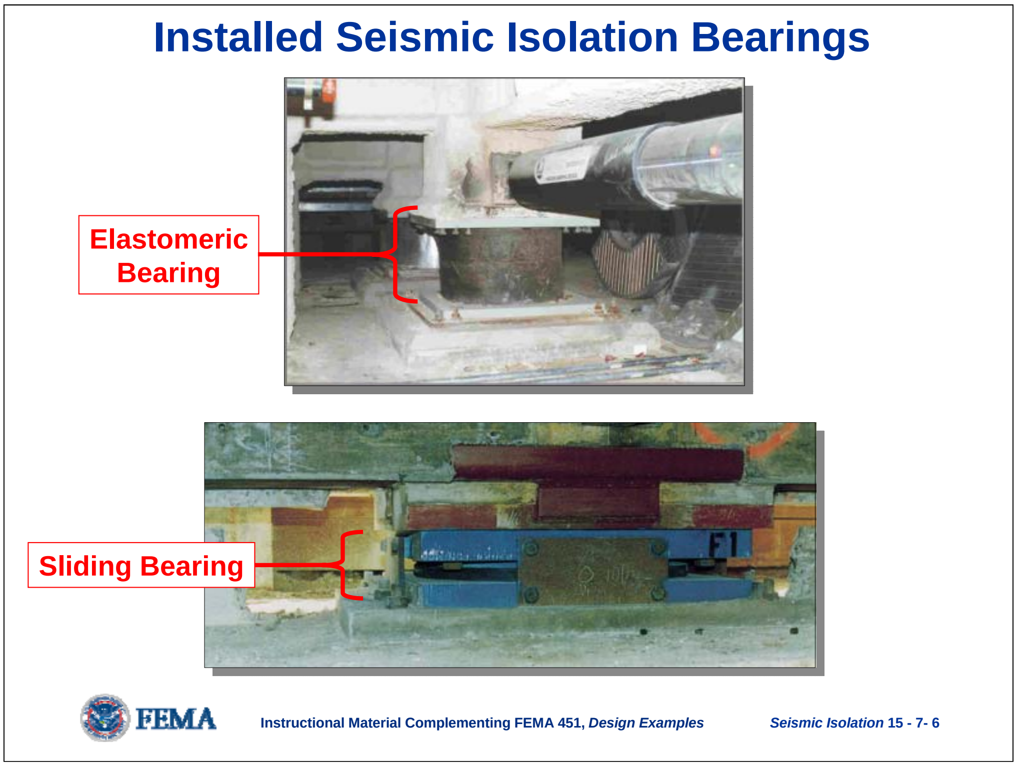
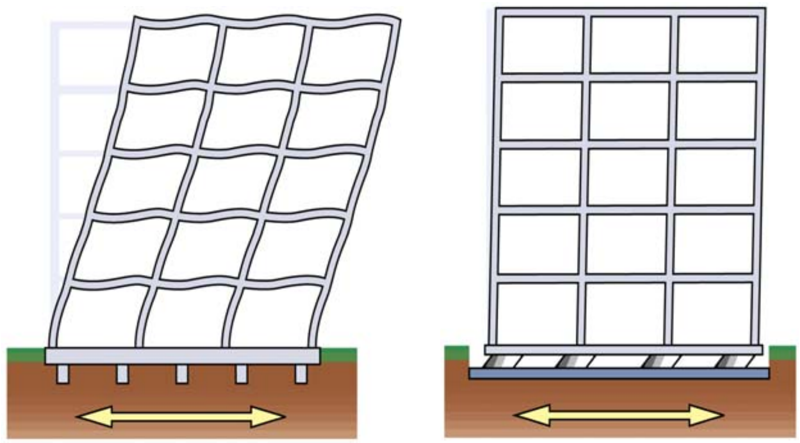
The two basic types of isolation bearings are sliding bearings and elastomeric bearings. Typically, isolation systems consist of either elastomeric bearings alone or sliding bearings alone, although in some cases they have been combined.



The top photo shows an elastomeric bearing along with a supplemental fluid damper within an isolation system. The bottom photo shows a sliding bearing within an isolation system of a retrofitted building. The rectangular plate connecting the top and bottom of the sliding bearing provides temporary restraint while the isolation system is being installed.

Behavior of Building Structure with Base Isolation System



Conventional Structure **Base-Isolated Structure**

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Qualitatively, a conventional structure experiences deformations within each story of the structure (i.e., interstory drifts) and amplified accelerations at upper floor levels. In contrast, isolated structures experience deformation primarily at the base of the structure (i.e., within the isolation system) and the accelerations are relatively uniform over the height.

Objectives of Seismic Isolation Systems

- Enhance performance of structures at all hazard levels by:
  - Minimizing interruption of use of facility (*e.g., Immediate Occupancy Performance Level)*
  - Reducing damaging deformations in structural and nonstructural components
  - Reducing acceleration response to minimize contents-related damage

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Characteristics of Well-Designed Seismic Isolation Systems

- Flexibility to increase period of vibration and thus reduce force response
- Energy dissipation to control the isolation system displacement
- Rigidity under low load levels such as wind and minor earthquakes

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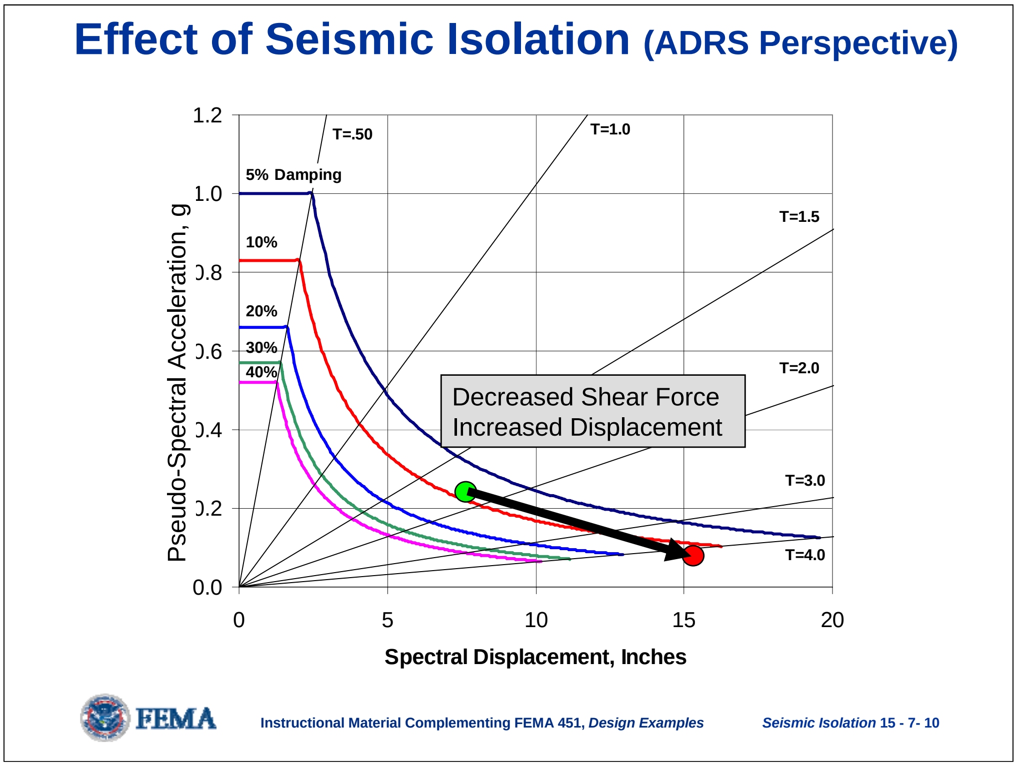
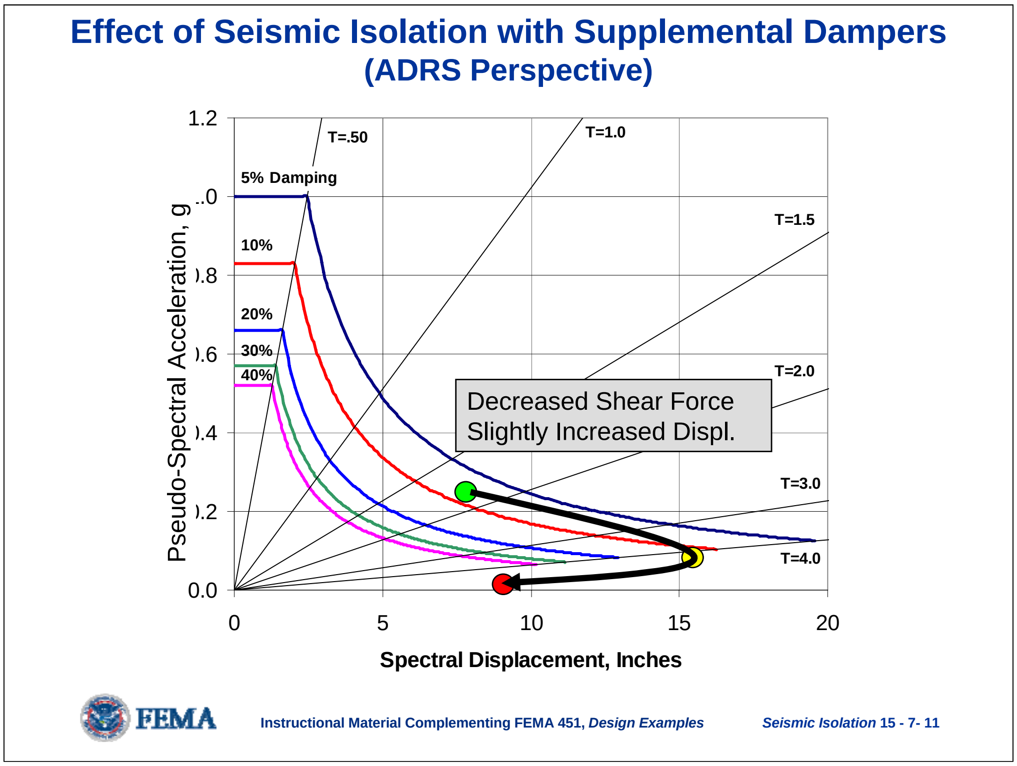
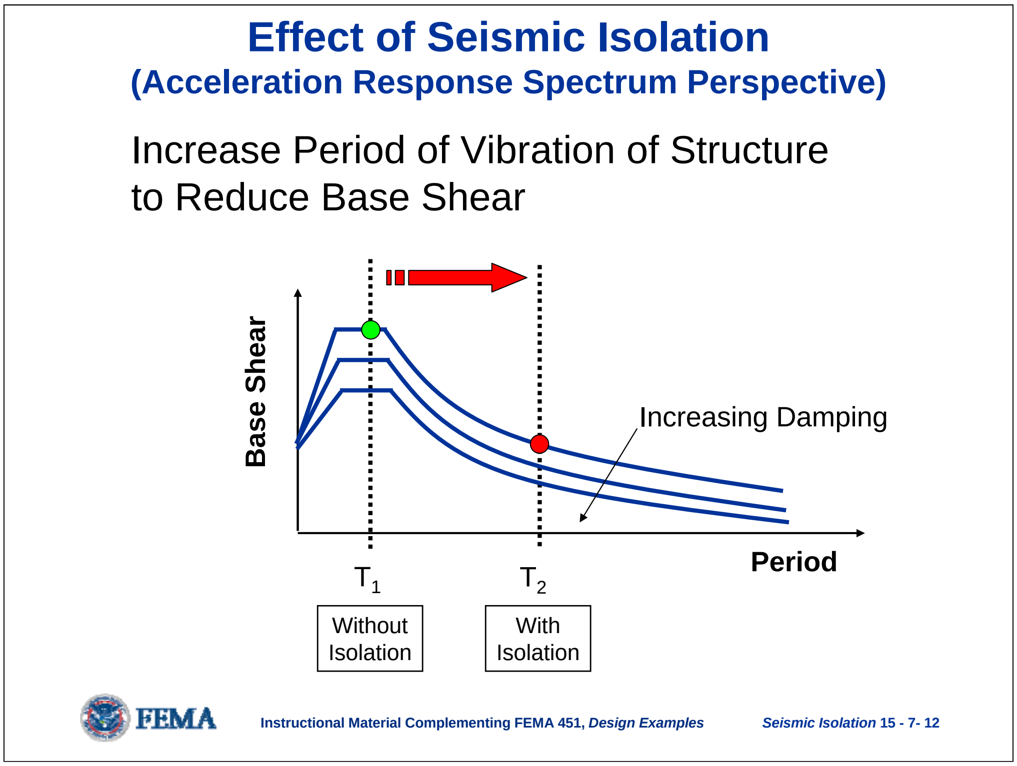


This slide shows a series of elastic design response spectra in the form of ADRS curves. In an ADRS spectrum, lines of constant period radiate out from the origin. A SDOF elastic structure having a natural period of 1.5 seconds and a damping ratio of 5% has a peak pseudo-acceleration and displacement response as indicated by the green circle. An isolation system is installed such that the natural period increases to 3.0 seconds (approximately 75% reduction in stiffness), resulting in an increase in peak displacement and reduction in peak pseudo-acceleration (and thus a reduction in shear force) as indicated by the red circle. The increased displacement occurs across the isolation system rather than within the structure. As the arrow indicates, the response moves along the 5%-damped design response spectrum.



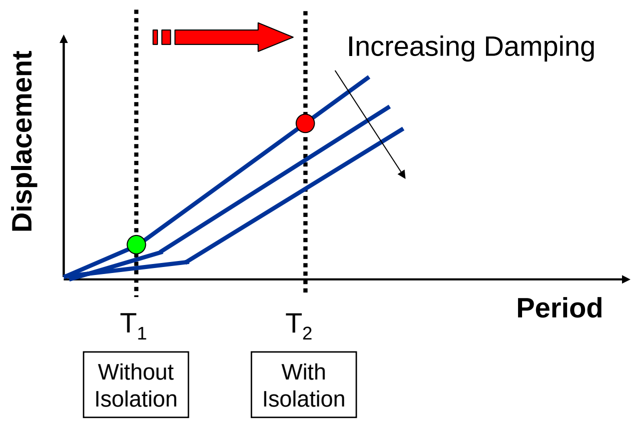
A SDOF elastic structure having a natural period of 1.5 seconds and a damping ratio of 5% has a peak pseudo-acceleration and displacement response as indicated by the green circle. An isolation system is installed such that the natural period increases to 3.0 seconds (approximately 75% reduction in stiffness) and the damping ratio increases to 30%, resulting in a slightly increased peak displacement and a reduction in peak pseudo-acceleration (and thus a reduction in shear force) as indicated by the red circle. The increased displacement occurs across the isolation system rather than within the structure. As the arrow indicates, the response first moves along the 5%-damped design response spectrum due to the reduced stiffness and then along the constant natural period line due to the increased damping.



This slide shows typical acceleration design response spectra for three different damping levels. The major effect of seismic isolation is to increase the natural period which reduces the acceleration and thus force demand on the structure. In terms of energy, an isolation system shifts the fundamental period of a structure away from the strongest components in the earthquake ground motion, thus reducing the amount of energy transferred into the structure (i.e., an isolation system “reflects” the input energy away from the structure). The energy that is transmitted to the structure is largely dissipated by efficient energy dissipation mechanisms within the isolation system.

Effect of Seismic Isolation
(Displacement Response Spectrum Perspective)

Increase of period increases displacement demand (now concentrated at base)



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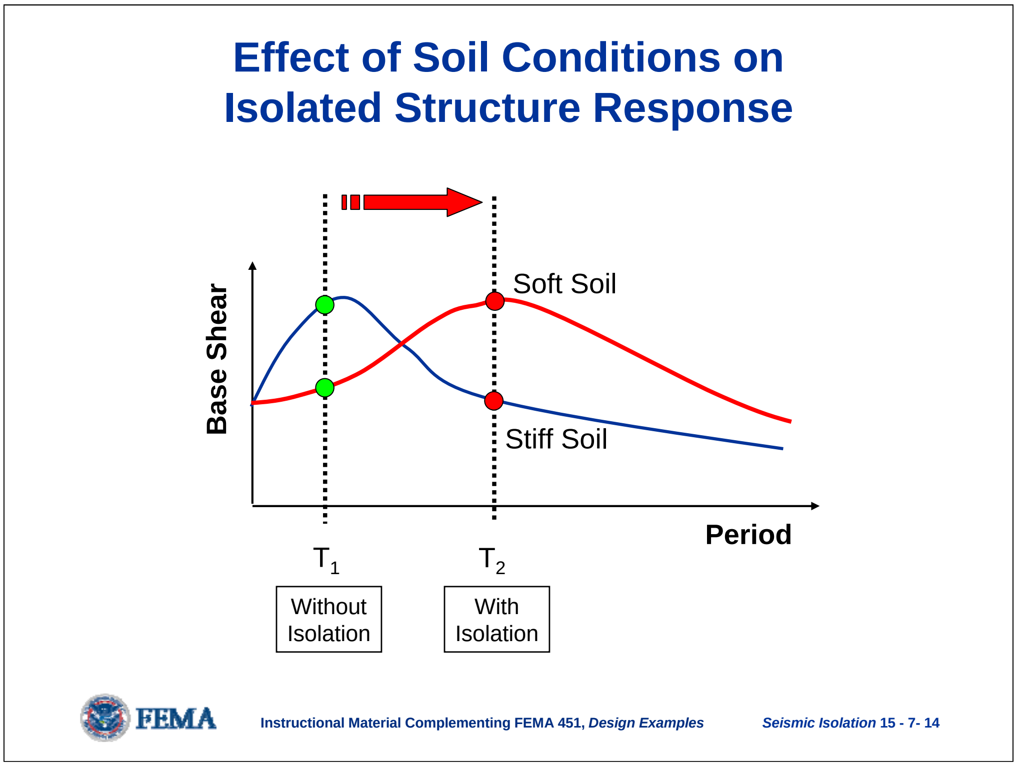
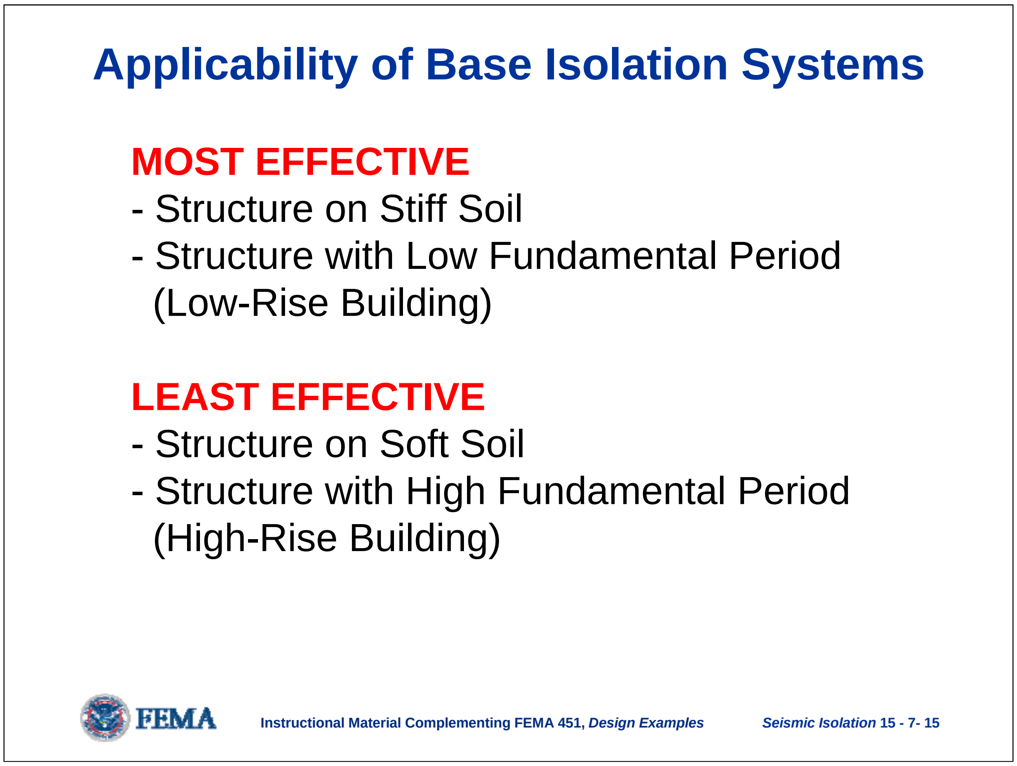
This slide shows typical displacement design response spectra for three different damping levels. The major effect of seismic isolation is to increase the natural period which increases the displacement demand; however, the displacement demand is shifted from the superstructure to the isolation system.



Softer soils tend to produce ground motion at higher periods which in turn amplifies the response of structures having high periods. Thus, seismic isolation systems, which have a high fundamental period, are not well-suited to soft soil conditions. Mexico City is a good example of a region with soft soil conditions; the fundamental natural period of the soil in Mexico City tends to be approximately 2 seconds.



Stiff structures are particularly well-suited to base isolation since they move from the high acceleration region of the design spectrum to the low acceleration region. In addition, for very stiff structures, the excitation of higher mode response is inhibited since the superstructure higher mode periods may be much smaller than the fundamental period associated with the isolation system.

First Implementation of Seismic Isolation

Foothill Community Law and Justice Center,
Rancho Cucamonga, CA

- Application to *new building* in 1985
- 12 miles from San Andreas fault
- Four stories + basement + penthouse
- Steel braced frame
- Weight = 29,300 kips
- 98 High damping elastomeric bearings
- 2 sec fundamental lateral period
- 0.1 sec vertical period
- +/- 16 inches displacement capacity
- Damping ratio = 10 to 20%
  (dependent on shear strain)

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Application of Seismic Isolation to Retrofit Projects

Motivating Factors:

- Historical Building Preservation
  (minimize modification/destruction of building)

- Maintain Functionality
  (building remains operational after earthquake)

- Design Economy
  (seismic isolation may be most economic solution)

- Investment Protection
  (long-term economic loss reduced)

- Content Protection
  (Value of contents may be greater than structure)

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Example of Seismic Isolation Retrofit

U.S. Court of Appeals,
San Francisco, CA

- Original construction started in 1905
- Significant historical and architectural value
- Four stories + basement
- Steel-framed superstructure
- Weight = 120,000 kips
- Granite exterior & marble, plaster, and hardwood interior
- Damaged in 1989 Loma Prieta EQ
- Seismic retrofit in 1994
- 256 Sliding bearings (FPS)
- Displacement capacity = +/-14 in.

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Types of Seismic Isolation Bearings

Elastomeric Bearings

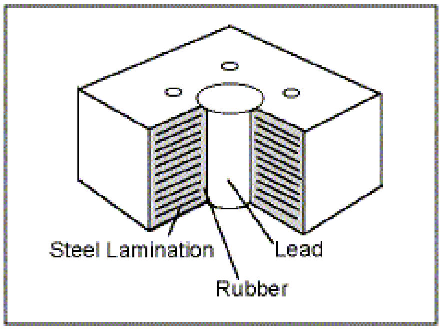
- Low-Damping Natural or Synthetic Rubber Bearing
- High-Damping Natural Rubber Bearing
- Lead-Rubber Bearing
  (Low damping natural rubber with lead core)

Sliding Bearings

- Flat Sliding Bearing
- Spherical Sliding Bearing

The major types of seismic isolation bearings are listed in this slide. Other isolation systems exist but have seen little to no implementation.

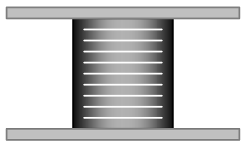
Geometry of Elastomeric Bearings



Major Components:
- Rubber Layers: Provide lateral flexibility
- Steel Shims: Provide vertical stiffness to support building weight while limiting lateral bulging of rubber
- Lead plug: Provides source of energy dissipation

Elastomeric bearings consist of a series of alternating rubber and steel layers. The rubber provides lateral flexibility while the steel provides vertical stiffness. In addition, rubber cover is provided on the top, bottom, and sides of the bearing to protect the steel plates. In some cases, a lead cylinder is installed in the center of the bearing to provide high initial stiffness and a mechanism for energy dissipation.

Low Damping Natural or Synthetic Rubber Bearings



Linear behavior in shear for shear strains up to and exceeding 100%.

Damping ratio = 2 to 3%

Advantages:
- Simple to manufacture
- Easy to model
- Response not strongly sensitive to rate of loading, history of loading, temperature, and aging.

Disadvantage:
Need supplemental damping system

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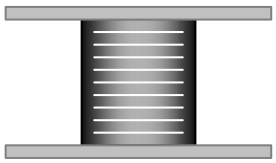
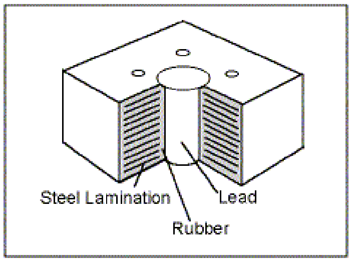
High-Damping Natural Rubber Bearings



- Maximum shear strain = 200 to 350%
- Damping increased by adding extrafine carbon black, oils or resins, and other proprietary fillers
- Damping ratio = 10 to 20% at shear strains of 100%
- Shear modulus = 50 to 200 psi
- Effective Stiffness and Damping depend on:
  - Elastomer and fillers
  - Contact pressure
  - Velocity of loading
  - Load history (scragging)
  - Temperature

The dynamic properties of high damping rubber bearings tend to be strongly sensitive to loading conditions. For example, high damping rubber bearings are subjected to scragging. Scragging is a change in behavior (reduction in stiffness and damping) during the initial cycles of motion with the behavior stabilizing as the number of cycles increases. The behavior under unscragged (virgin) conditions can be appreciably different from that under scragged (subjected to strain history) conditions. Over time (hours or days), the initial bearing properties are recoverable.

Lead-Rubber Bearings



- Solid lead cylinder is press-fitted into central hole of elastomeric bearing
- Lead yield stress = 1500 psi (results in high initial stiffness)
- Invented in 1975 in New Zealand and used extensively in New Zealand, Japan, and the United States.
- Low damping rubber combined with central lead core
- Shear modulus = 85 to 100 psi at 100% shear strain
- Maximum shear strain = 125 to 200% (since max. shear strain is typically less than 200%, variations in properties are not as significant as for high-damping rubber bearings)
- Yield stress reduces with repeated cycling due to temperature rise
- Hysteretic response is strongly displacement-dependent

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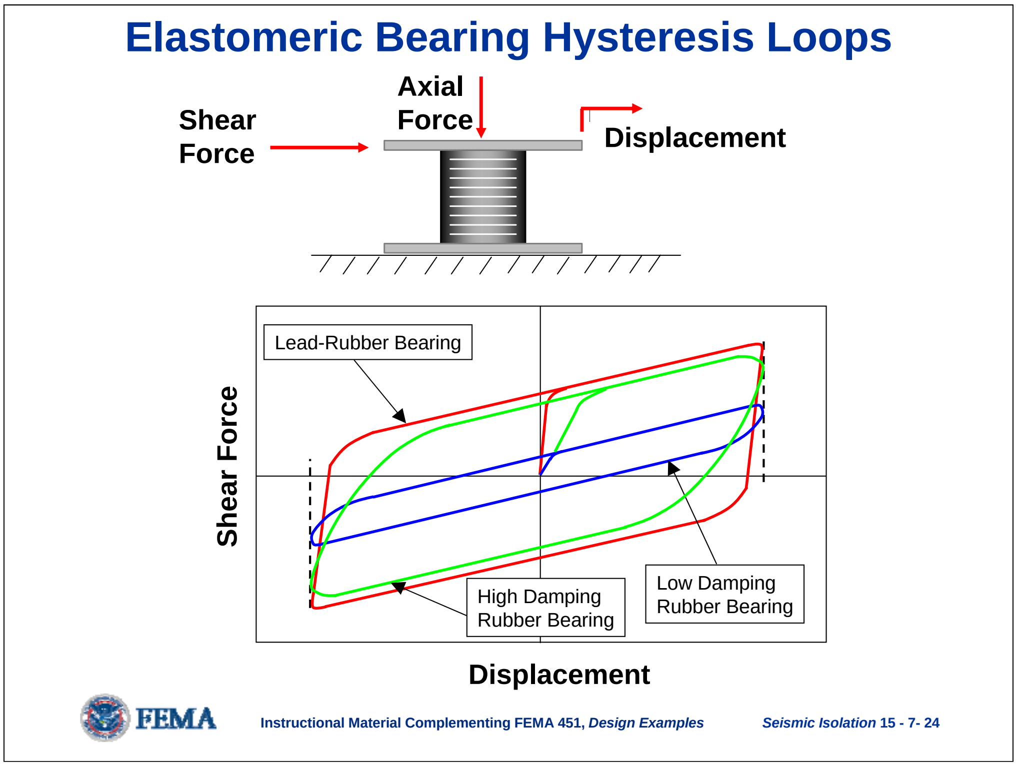
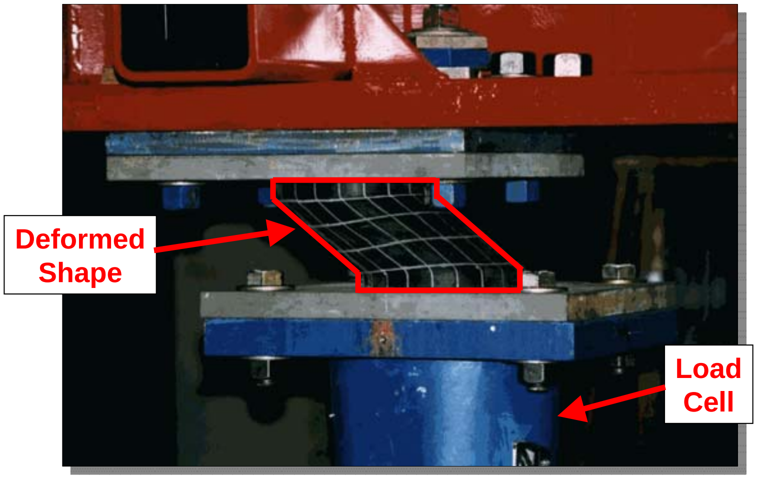
Lead-rubber bearings include a central lead plug that is used to increase the initial stiffness of the bearing (provides wind loading restraint) and increase the energy dissipation capacity of the bearing. After the lead yields, it dissipates energy as it is cycled. Fatigue of the lead is not a concern since lead recrystallizes at normal temperatures.



The behavior of elastomeric bearings can be determined via experimental testing in which the bearings are subjected to constant axial load and sinusoidal lateral load. Low damping rubber bearings produce narrow hysteresis loops due to their inability to dissipate significant amounts of energy. In contrast, high damping and lead-rubber bearings produce wider hysteresis loops due to their ability to dissipate significant amounts of energy. Note that, for a given peak displacement, lead rubber bearings exhibit higher initial stiffness and more loop area (energy dissipation) than high damping rubber bearings. In general, elastomeric bearings exhibit high stiffness at low shear strains, reduced stiffness at intermediate strains, and increased stiffness at high strains.

Shear Deformation of Elastomeric Bearing



- Bearing Manufactured by Scougal Rubber Corporation.
- Test Performed at SUNY Buffalo.
- Shear strain shown is approximately 100%.

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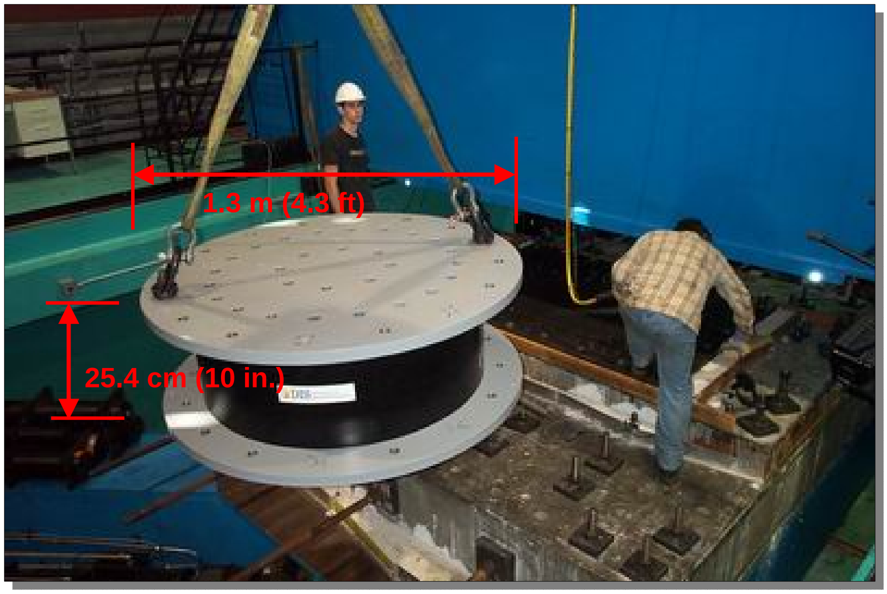
A bearing under test is shown. The red outline indicates the deformed shape of the bearing.

Full-Scale Bearing Prior to Dynamic Testing



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The bearing shown is being prepared for experimental testing at the Caltrans Seismic Response Modification Device (SRMD) Test Facility at UC San Diego. The facility was developed for full-scale testing of seismic isolation bearings for application to bridge structures.

Cyclic Testing of Elastomeric Bearing

Bearing Manufactured by
Dynamic Isolation Systems Inc.

Testing of Full-Scale Elastomeric Bearing at UC San Diego
- Compressive load = 4000 kips
- 400% Shear Strain [1.0 m (40 in.) lateral displacement]
- Video shown at 16 x actual speed of 1.0 in/sec

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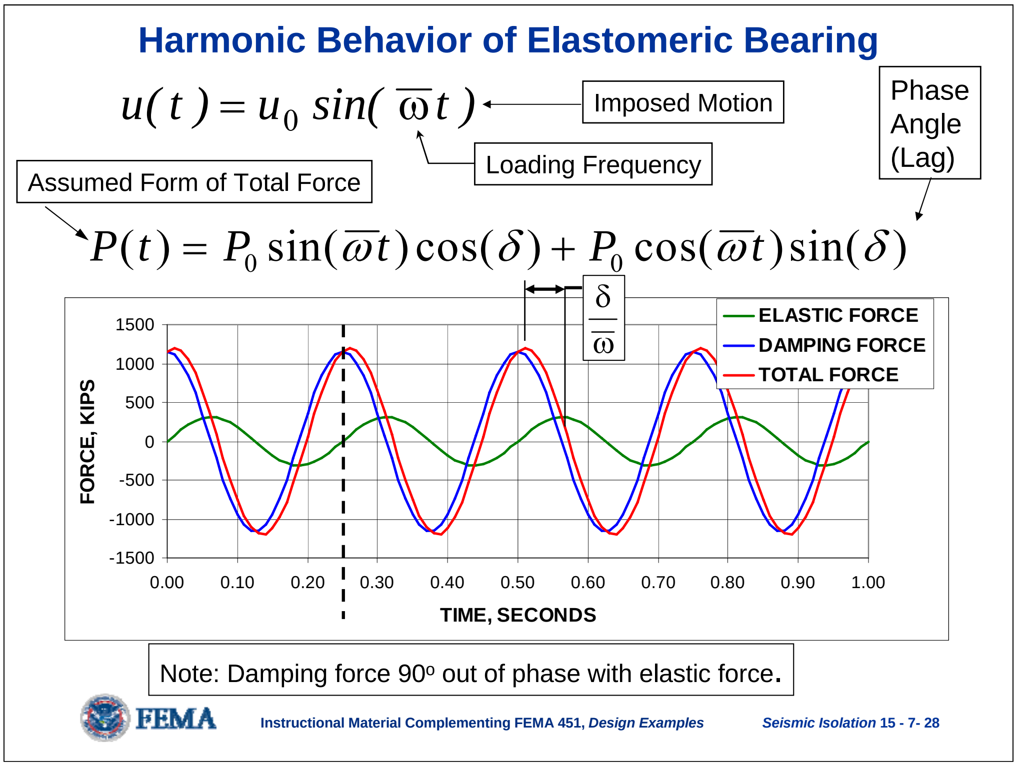
The bearing (from the previous slide) installed in the Caltrans Seismic Response Modification Device (SRMD) Test Facility at UC San Diego.



The frequency-dependent behavior of elastomeric bearings is typically obtained via harmonic testing. In this test, the bearing is subjected to a constant axial compressive load and a lateral harmonic displacement is applied at a given frequency. The force required to impose the motion is measured. The measured force is out-of-phase with respect to the displacement due to the damping within the bearing. If the bearing is idealized as a viscoelastic element, the elastic force is proportional to displacement, the damping force is proportional to velocity, and the measured (or total) force is related to both the displacement and velocity.

$$P(t) = K_S u(t) + C\dot{u}(t)$$

$$K_S = \frac{P_0}{u_0} cos(\delta)$$

Storage Stiffness

$$K_L = \frac{P_0}{u_0} sin(\delta)$$

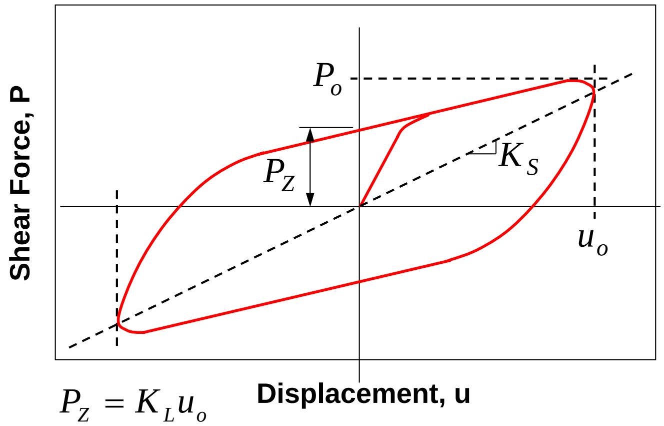
Loss Stiffness

$$C = \frac{K_L}{\varpi}$$

Damping Coeff.

$$\delta = \sin^{-1}\left(\frac{P_Z}{P_0}\right)$$

Phase Angle



$$\xi = \frac{1}{2} tan(\delta)$$

$$P_Z = K_L u_o$$

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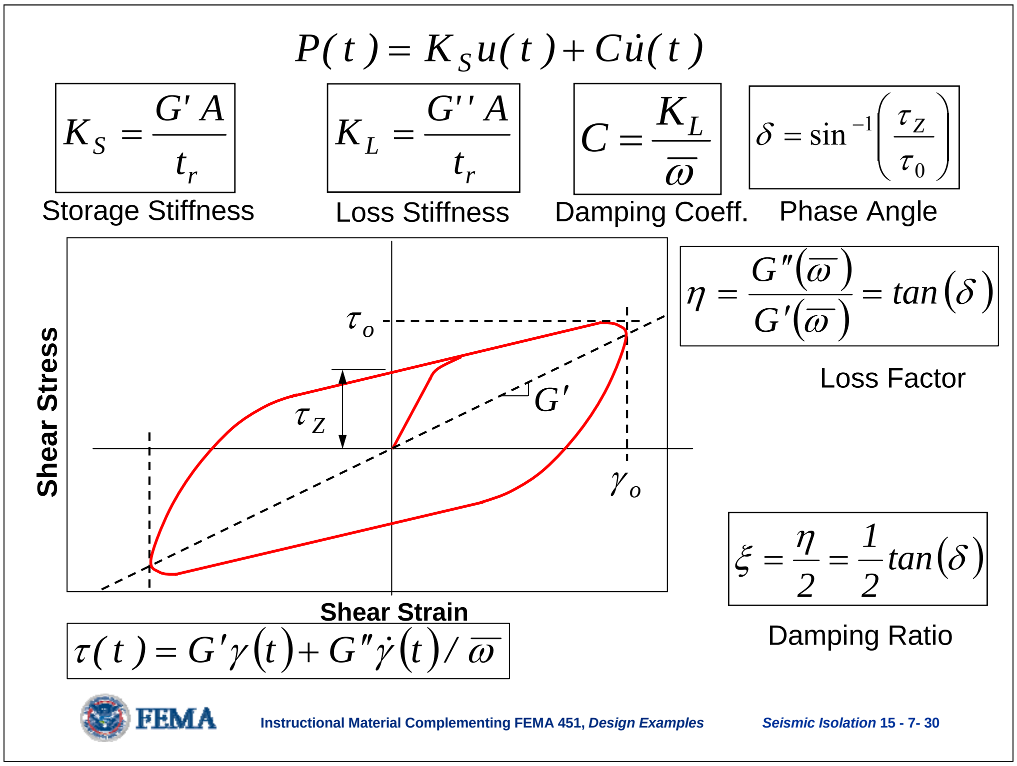
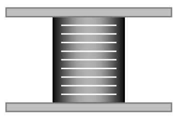
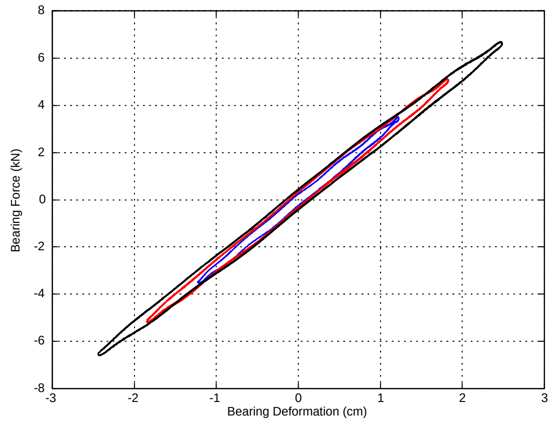
If the bearing is idealized as a viscoelastic element, the total bearing force is related to both the displacement and velocity. The storage stiffness characterizes the ability of the bearing to store energy. The loss stiffness and damping coefficient characterize the ability of the bearing to dissipate (or lose) energy. The phase angle indicates the degree to which the bearing stores and dissipates energy. For example, if the phase angle is 90 degrees, the storage stiffness is zero and thus the bearing acts as a pure energy dissipation element (i.e., a linear viscous dashpot). Conversely, if the phase angle is 0 degrees, the loss stiffness is zero and the bearing acts as a pure energy storage element (i.e., a linear spring). In terms of the bearing hysteresis loop, the storage stiffness is the slope of the loop at the maximum displacement. The width of the loop at zero displacement is proportional to the loss stiffness. The area within the loop, which is also proportional to the loss stiffness, is equal to the energy dissipated per cycle.



In terms of the damper stress-strain hysteresis loop, the storage modulus (which is proportional to the storage stiffness) is the slope of the loop at the maximum strain. The width of the loop at zero displacement is proportional to the loss modulus (which, in turn, is proportional to the loss stiffness). The area within the loop, which is also proportional to the loss modulus, is equal to the energy dissipated per cycle. Note that the shear and loss moduli are material properties whereas the storage and loss stiffness are damper properties (i.e., the storage and loss stiffness depend on the bearing geometry through the bearing bonded shear area, *A*, and total rubber thickness, t_r).

Experimental Hysteresis Loops of Low Damping Rubber Bearing





Low Damping Rubber Bearing
- Reduced scale bearing for ¼-scale building frame
- Diameter and height approx. 5 in.
- Prototype fundamental period of building = 1.6 sec

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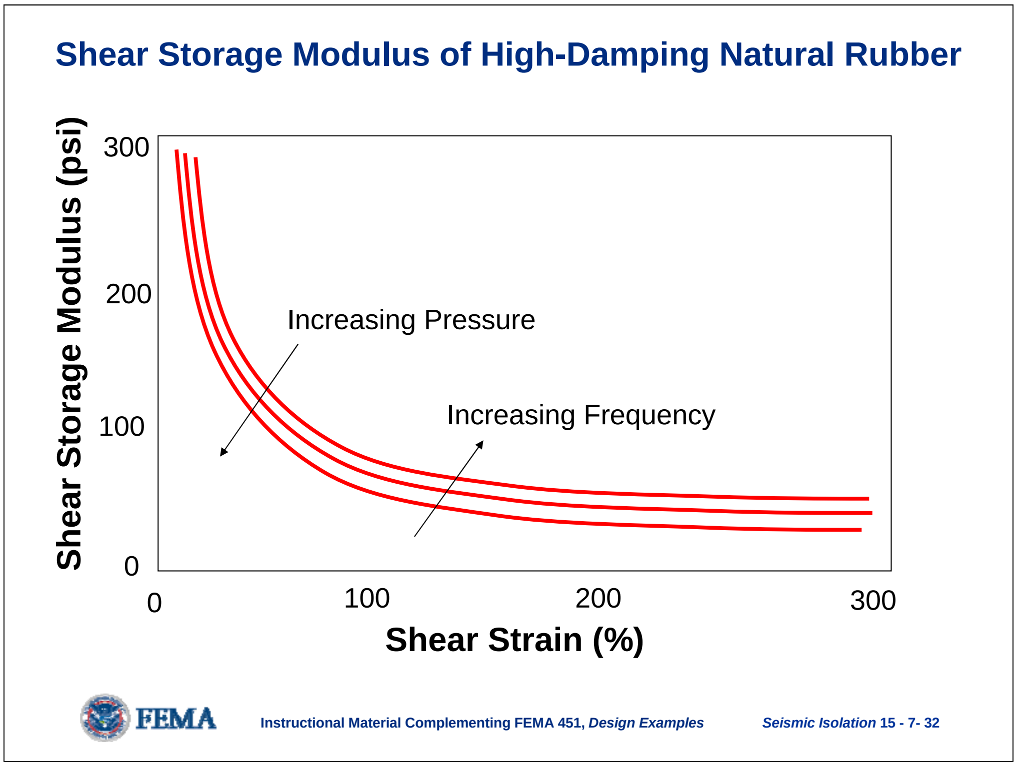
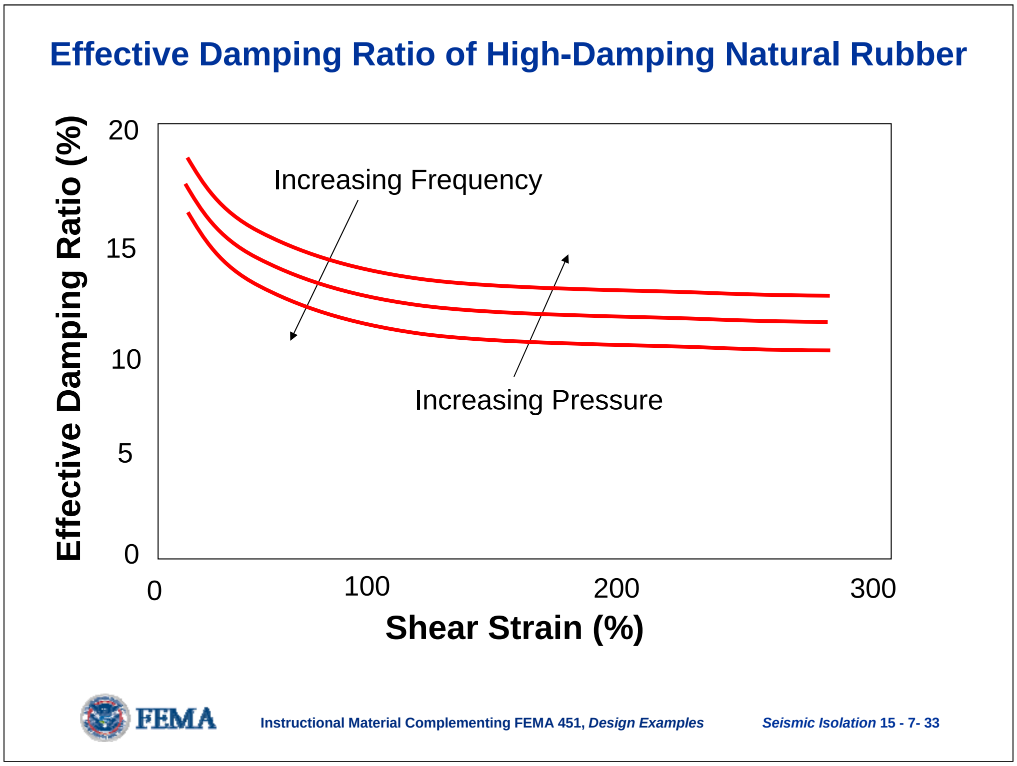
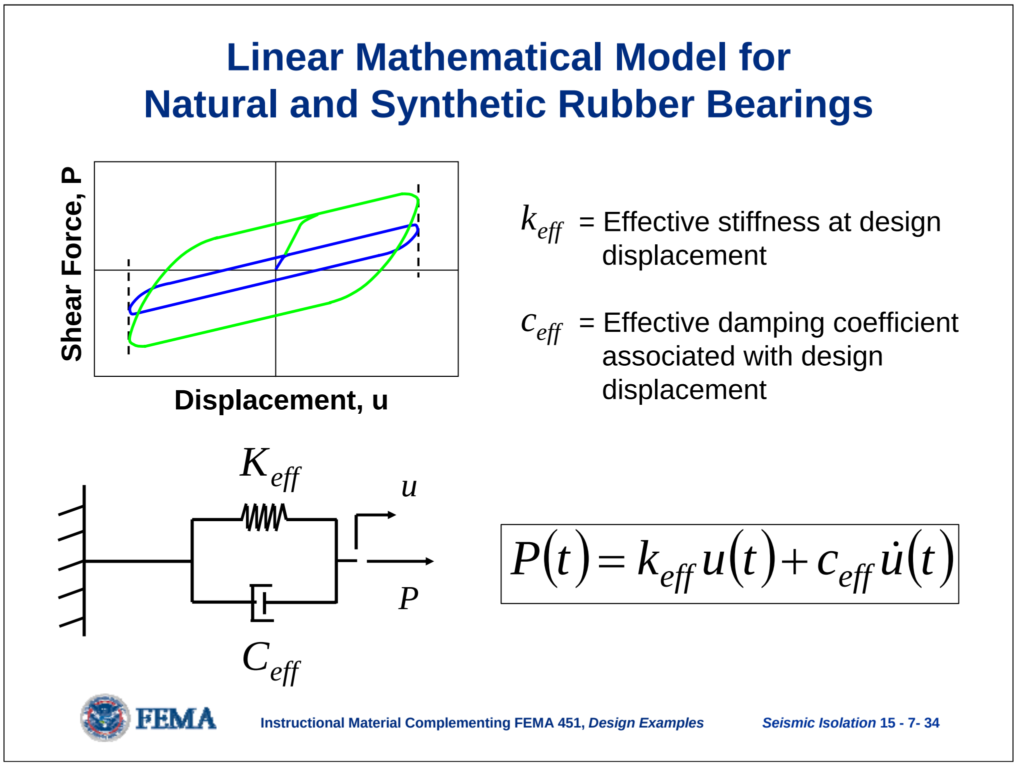
The hysteresis loop shown is for a reduced-scale bearing. The bearing was designed for isolation of a 1:4-scale steel moment frame. For reduced-scale dynamic testing, an attempt to produce a large fundamental period results in very flexible bearings (large aspect ratio) due to the relatively low mass supported by the bearings. The flexibility leads to potential instability problems. Thus, the prototype period given above is not very large.



The stiffness of high damping rubber bearings decreases with increasing shear strain (and, then, although not shown here, increases again at higher shear strains). The increased stiffness at high shear strains is sometimes regarded as a fail-safe mechanism.

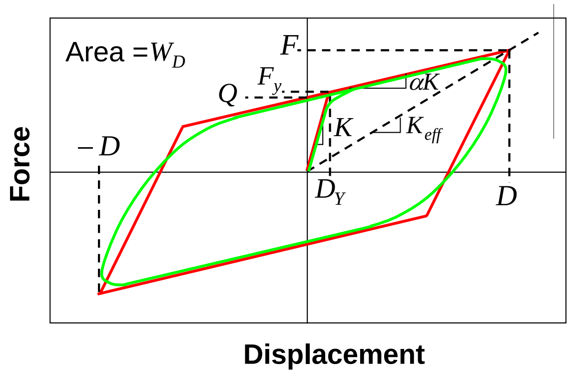


The damping of high damping rubber bearings decreases with increasing shear strain but tends to become relatively constant at high shear strains.



An equivalent linear mathematical model of an isolation bearing consists of an elastic spring in parallel with a viscous dashpot. The effective properties are determined at the design displacement and at the fundamental period of the structure.

Equivalent Linear Properties from Idealized Bilinear Hysteresis Loop



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

$$\boxed{k_{eff} = \frac{F}{D} = \alpha K + \frac{Q}{D}}$$

$$\xi_{eff} = \frac{W_D}{4\pi W_S}$$

$$W_S = \frac{1}{2} K_{eff} D^2$$

$$W_D = 4Q(D - D_Y)$$

If $Q >> D_Y$, then: $W_D \approx 4QD$

$$\boxed{\xi_{eff} = \frac{2Q(D - D_Y)}{\pi D(Q + \alpha K D)}}$$

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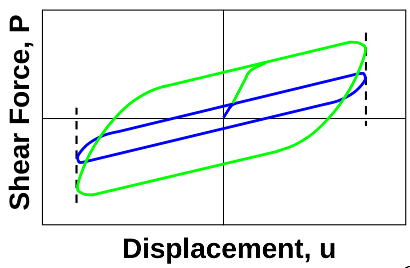
The equivalent linear properties (effective stiffness and damping ratio) are obtained by replacing the actual hysteresis loop obtained from a sinusoidal test with that corresponding to an idealized bilinear system. Typically, the replacement is done by equating the peak displacement, D, and area within the two loops, W_D. For the bilinear system, the characteristic strength, Q, is the intercept at zero displacement, the yield force, F_y, is the force corresponding to the yield displacement, D_y, and K is the initial elastic stiffness. Note that, due to the nonlinear nature of the bearing behavior, the effective bearing properties are displacement-dependent.

Refined Nonlinear Mathematical Model for Natural and Synthetic Rubber Bearings



α = Post-to-pre yielding stiffness ratio

P_y = Yield force

u_y = Yield displacement

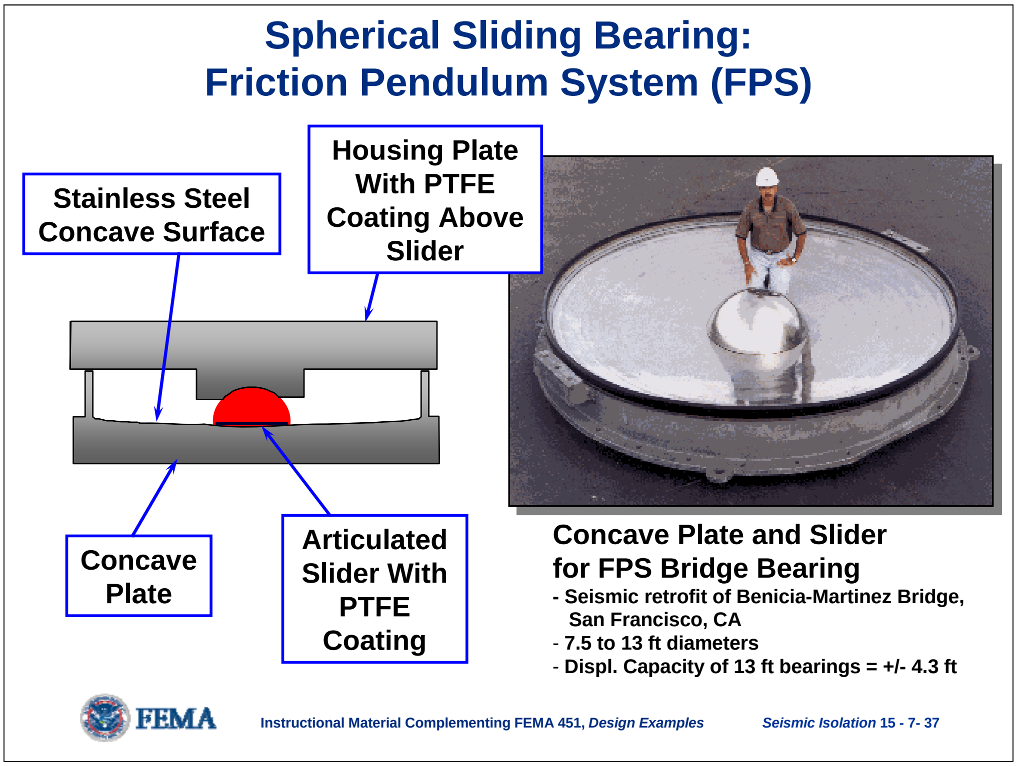
Z = Evolutionary variable

$\gamma, \beta, \eta, \theta$ = Calibration constants

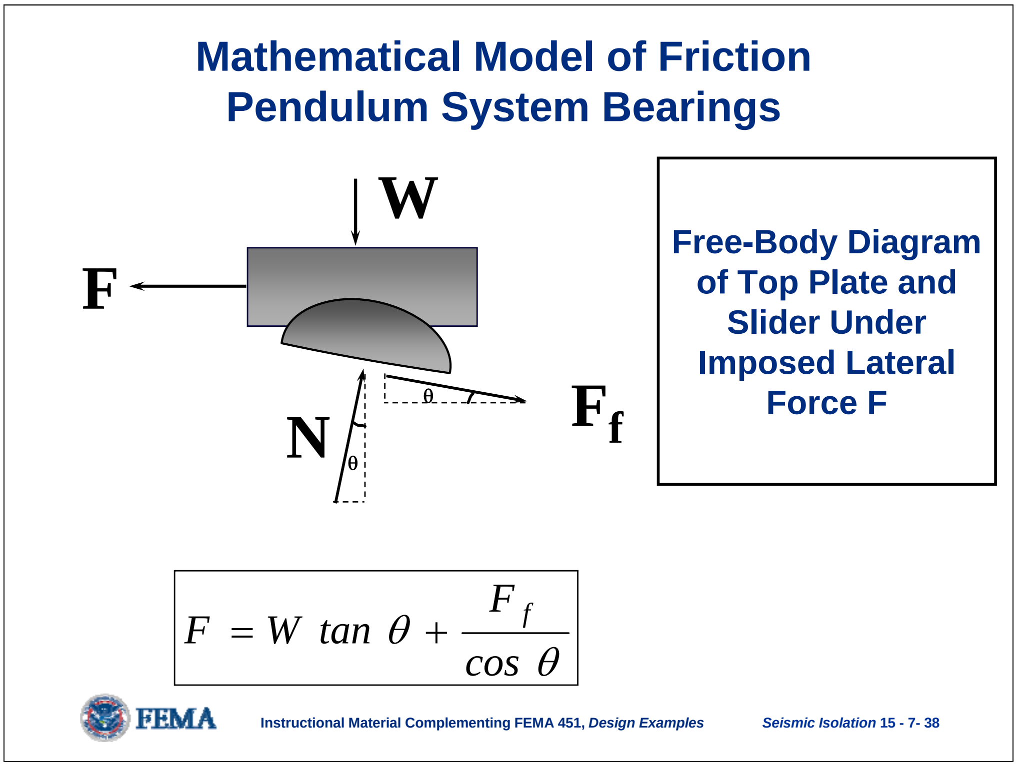
$$P(t) = \alpha \frac{P_y}{u_y} u(t) + (1-\alpha) P_y Z(t)$$ *Shear Force in Bearing*

$$u_y \dot{Z} + \gamma |\dot{u}| Z |Z|^{\eta-1} + \beta \dot{u} |Z|^{\eta} - \theta \dot{u} = 0$$ *Evolutionary Equation*

For more sophisticated analyses, a refined model of the bearings may be utilized in which the evolution of the hysteresis loop is characterized by an evolutionary variable. The model shown above is from Paolo and Wen (1994).

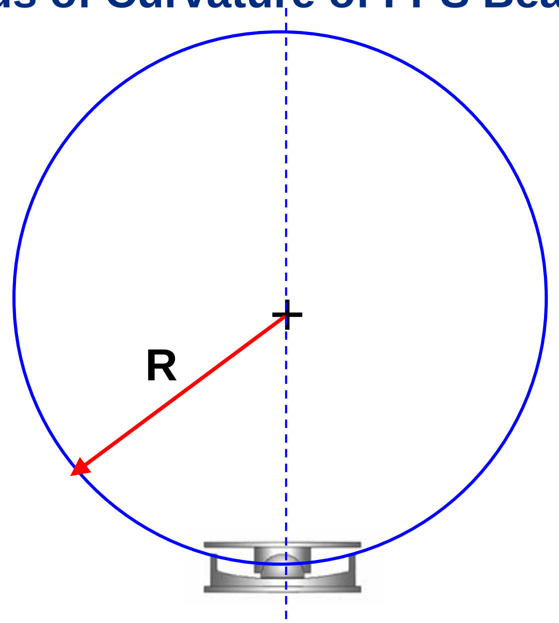


Sliding bearings typically utilize either spherical or flat sliding surfaces. The Friction Pendulum System (FPS) bearing utilizes a spherical surface and is the most widespread sliding seismic isolation bearing in use within the United States. In the figure and photograph shown, the sliding surface is shown concave up. In typical applications, the sliding surface is oriented concave down to minimize the possibility of debris collecting on the sliding surface. The articulated slider is faced with a PTFE (PolyTetraFlouroEthylene) coating. PTFE is a plastic material that may be unfilled (virgin) or filled (blended) with various materials (e.g., glass, carbon, bronze, graphite, etc.) to enhance its properties. A well-known PTFE material is "Teflon" which is manufactured by Dupont.



The lateral resistance of an FPS bearing is determined by applying a lateral load to the bearing and determining the resisting forces. The equation shown is obtained by establishing equilibrium in both the vertical and horizontal directions and neglecting higher order terms.

Radius of Curvature of FPS Bearings



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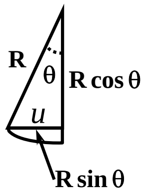
The geometry of the spherical sliding surface is defined by a circle of radius *R*. This radius is "radius of curvature" of the bearing sliding surface. If the circle is rotated above a vertical axis (the dashed line), a spherical surface is formed. A portion of that surface represents the sliding surface of the bearing.

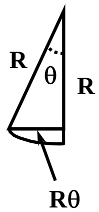
Mathematical Model of Friction Pendulum System Bearings



For u < 0.2R, θ is small (2% error in u)

$$\sin\theta = \theta - \frac{\theta^3}{3!} + \ldots \approx \theta$$

$$\cos\theta = 1 - \frac{\theta^2}{2!} + \ldots \approx 1$$



$$\theta \approx \frac{u}{R} \qquad N = \frac{W}{\cos\theta} \approx W$$

$$F_f = \mu N \; sgn(\dot{u})$$

$$\boxed{F = W\tan\theta + \frac{F_f}{\cos\theta}} \longrightarrow \boxed{F = \frac{W}{R}u + \mu W \; sgn(\dot{u})}$$

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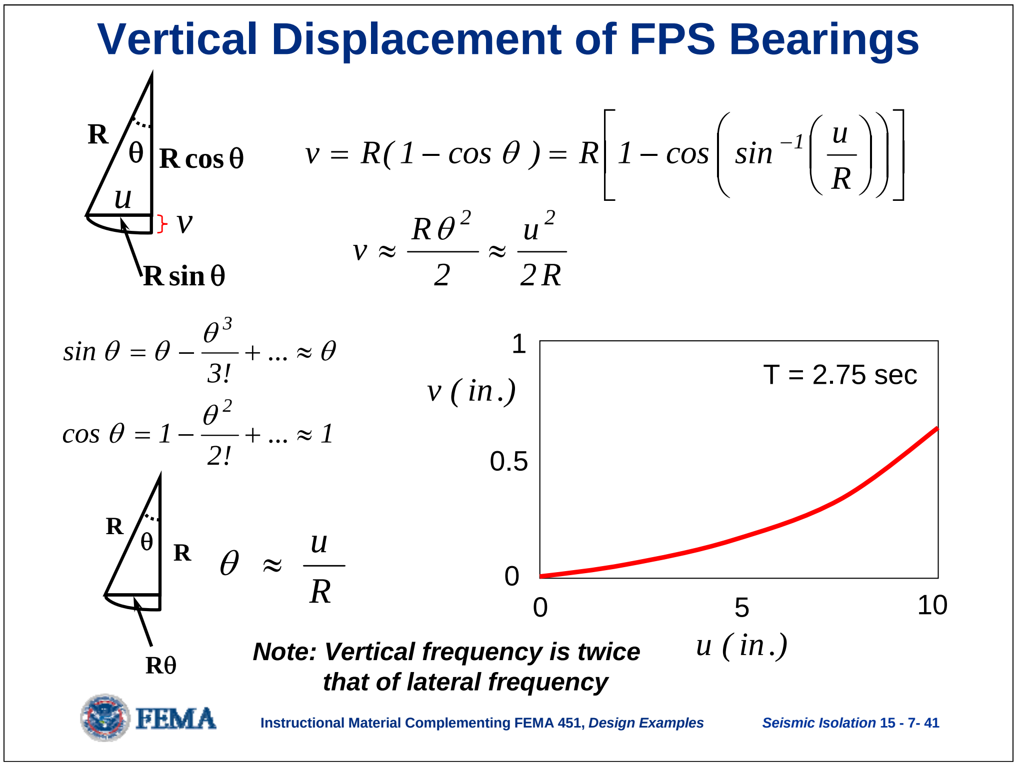
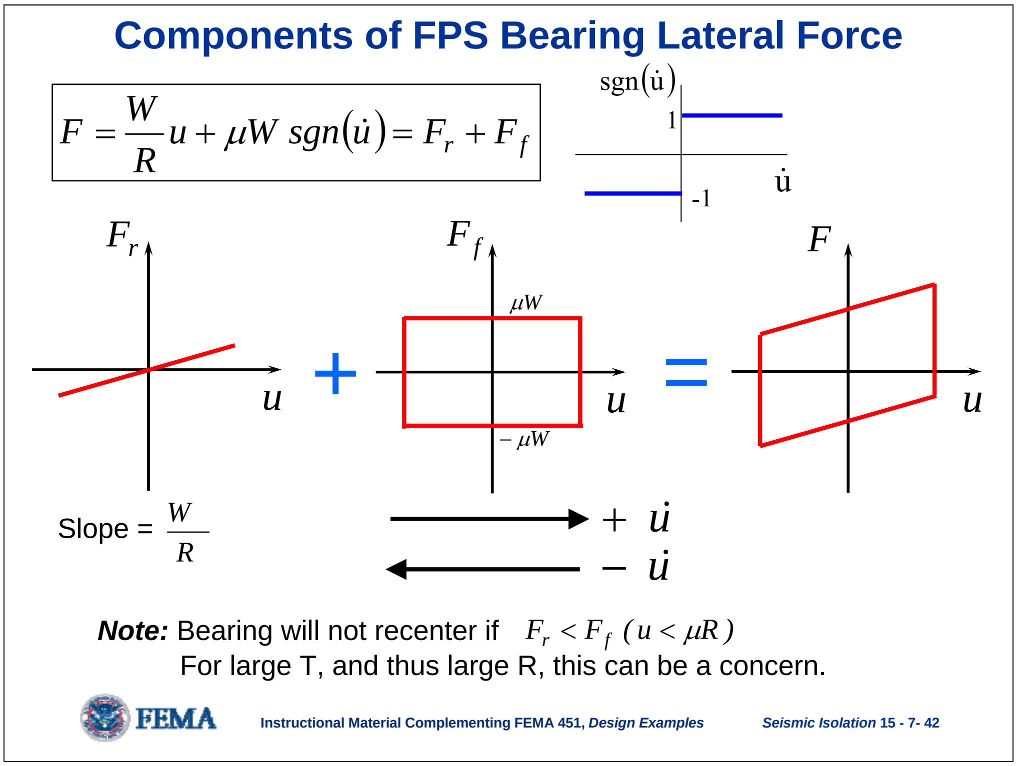
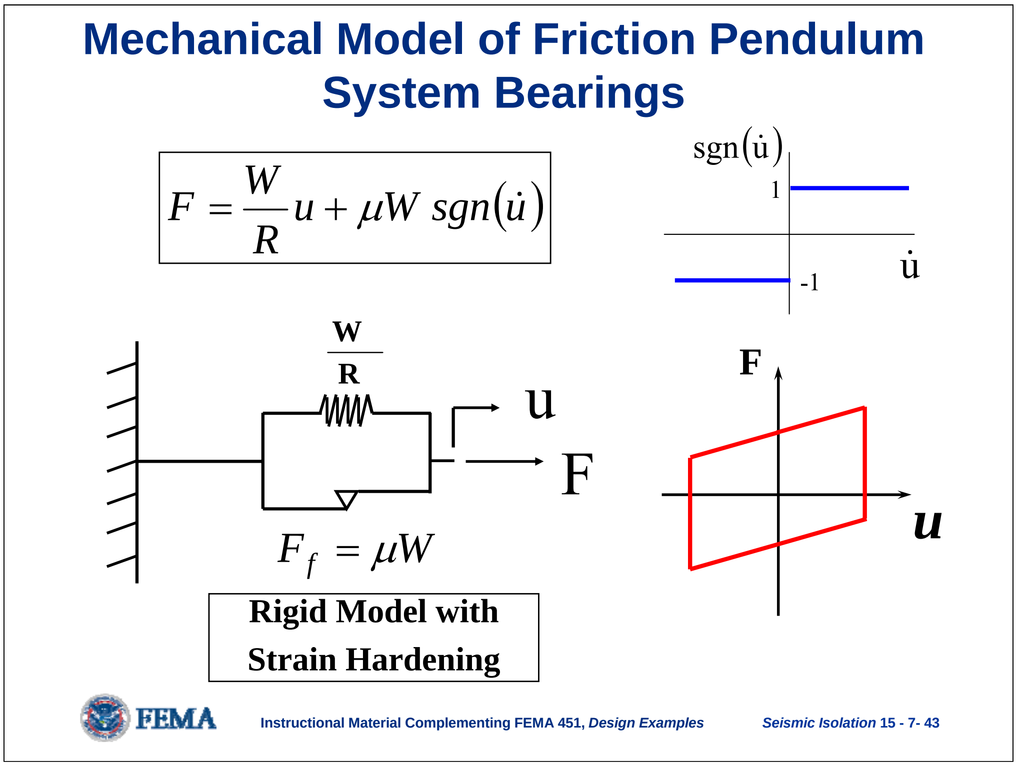
For practical lateral displacements, the angle θ associated with the translation of the bearing is small. Replacing the trigonometric functions with their small angle approximations leads to the final result shown. Note that the signum function, which gives the sign of the velocity, is used to define the direction of the friction force.



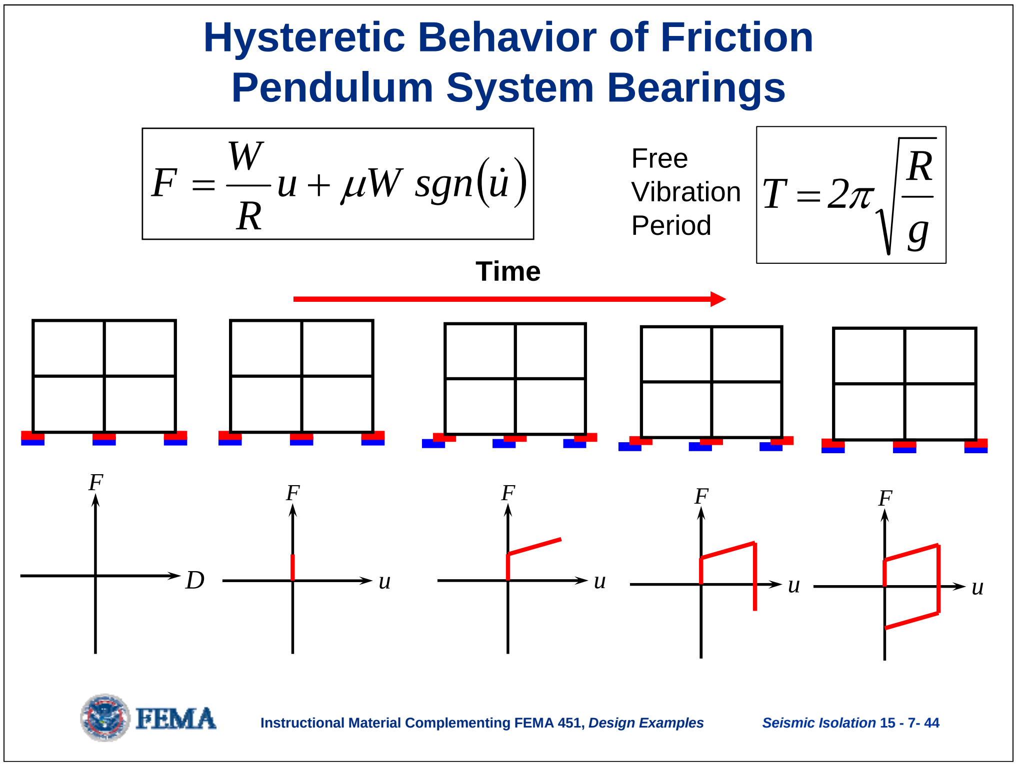
Due to the shape of the sliding surface, the lateral translation of the bearing is accompanied by vertical motion. The vertical motion is approximately proportional to the square of the lateral displacement and inversely proportional to the radius of curvature. As indicated by the plot, the vertical motion is generally insignificant in comparison to the lateral displacement. Interestingly, the spherical shape of the sliding surface results in a vertical frequency that is twice that of the lateral frequency (i.e., as the slider moves through one cycle laterally, it moves through two cycles vertically.)



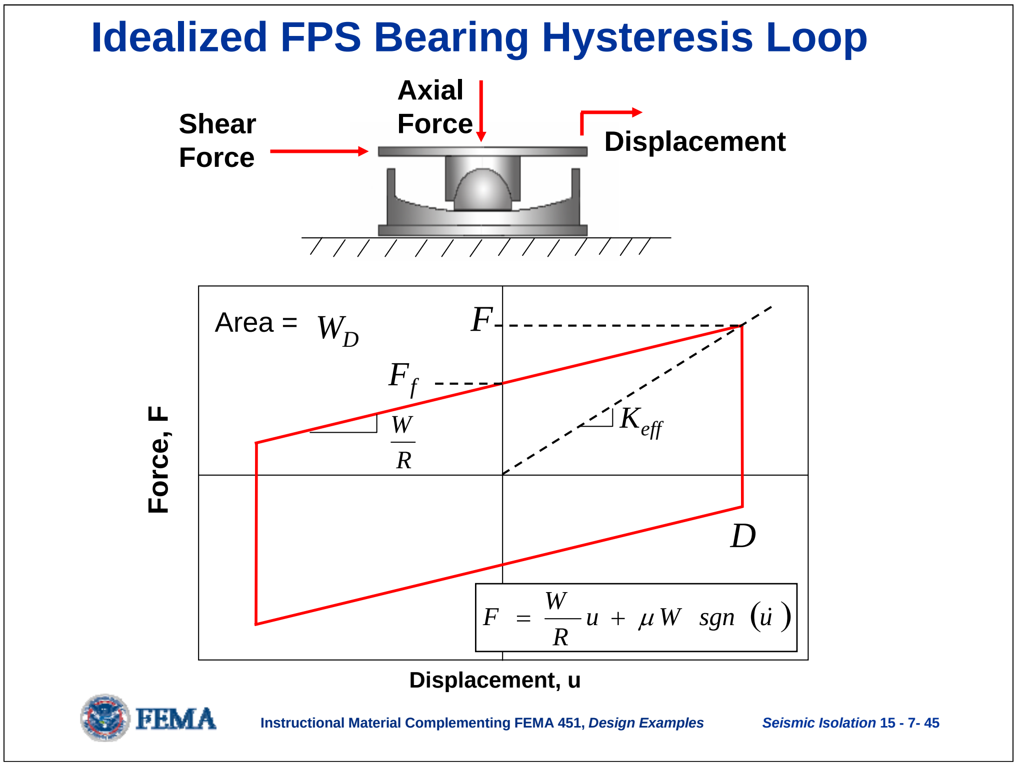
The bearing lateral force has two components, a restoring force due to the raising of the building mass along the sliding surface, and a friction force due to friction at the sliding interface. The restoring force provides stiffness while the friction force provides energy dissipation. The hysteresis loops of these two simple components may be combined to form the hysteresis loop of the bearing. As noted previously, the signum function returns the sign of its argument and thus can be used to define the direction of the friction force.



A simple mechanical model of the FPS bearing consists of a linear spring in parallel with a friction element.

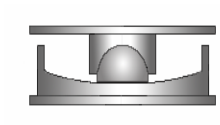


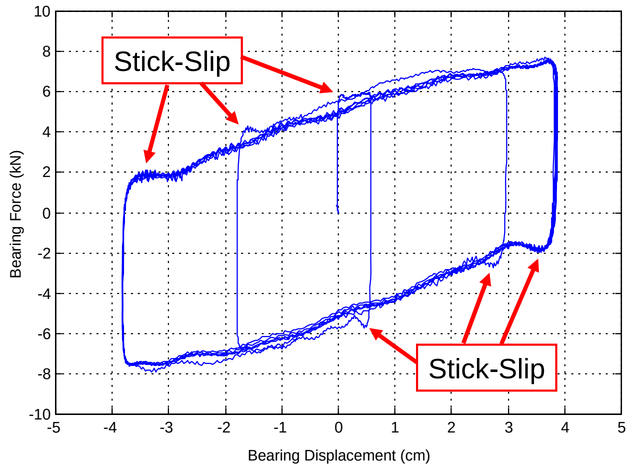
In this slide, an entire building supported on FPS bearings is considered. The progression of the isolation system hysteresis loop is shown for a half-cycle of motion. Assuming that the building superstructure behaves as a rigid body, the natural period of the isolated structure (i.e., the time for a full-cycle of motion) is controlled by the radius of curvature and is independent of the building weight. Thus, if the weight of the structure changes (e.g., storage facilities or tanks) or is different than assumed, the natural period will not change. Furthermore, the lateral force in each bearing is proportional to the weight carried by that bearing. Thus, the center of mass of the structure and the center of stiffness of the isolation system will coincide and therefore the torsional response of asymmetric buildings will be minimized.



An idealized FPS bearing hysteresis loop is shown. The validity of this loop depends on the assumptions made in developing the mathematical model (e.g., constant coefficient of friction).

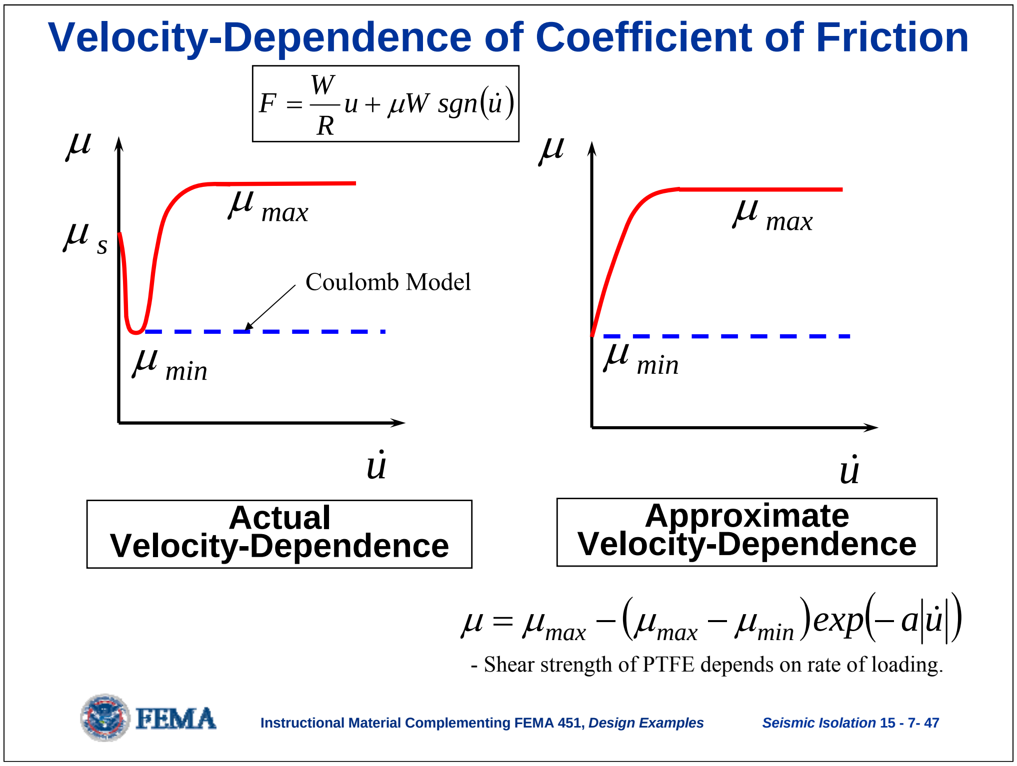
Actual FPS Bearing Hysteresis Loop



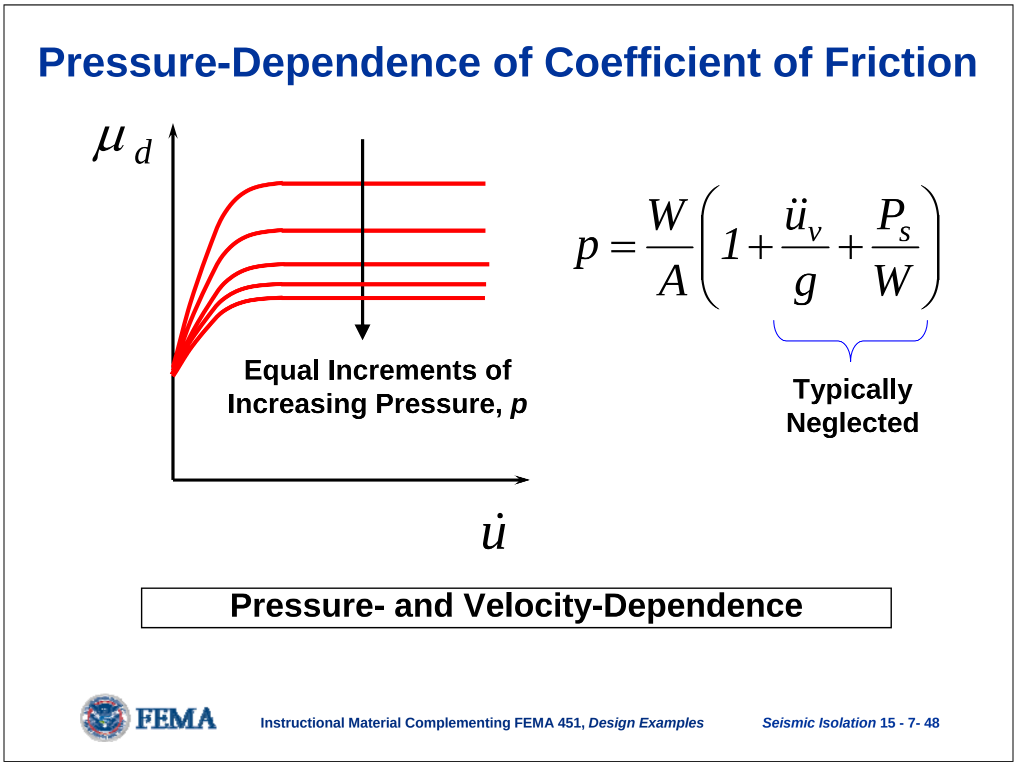


FPS Bearing
- Reduced-scale bearing for ¼-scale building frame
- R = 18.6 in; D = 11 in.; H = 2.5 in. (reduced scale)
- Prototype fundamental period of building = 2.75 sec (R = 74.4 in. = 6.2 ft)

The hysteresis loop of a reduced-scale bearing is shown. Note that the loop does not follow the exact shape of the idealized hysteresis loop, indicating that the developed model neglects certain phenomena (e.g., stick-slip behavior when the direction of motion changes). Also note that the natural period of the isolated building (assuming rigid superstructure) is dependent only on the radius of curvature of the bearings (i.e., to achieve an isolated period of 2.75 sec, R must be 6.2 ft).



Thus far, it has been assumed that the coefficient of friction is constant. In reality, the coefficient of friction is both velocity- and pressure-dependent. The velocity-dependence is illustrated in this slide and is due to the PTFE shear strength being dependent on the rate of loading. Prior to slippage, the static friction force associated with the static coefficient of friction must be overcome. Once slippage occurs, the friction force quickly drops to a minimum but then increases at higher velocities until it stabilizes at the maximum friction force. The mathematical model shown, which approximately accounts for the velocity-dependence, was developed from studies on virgin PTFE in contact with mirror-finish stainless steel. The simple Coulomb model of friction assumes that the sliding coefficient of friction has a constant value at all velocities.



The pressure-dependence of the coefficient of friction is illustrated in this slide. Note that the vertical pressure on a bearing supporting weight *W* consists of three components: (1) Pressure due to supported weight; (2) Pressure due to vertical acceleration of the supported weight; and (3) Pressure due to overturning moments. The last two components are typically neglected since they tend to be relatively small with respect to the first term.

Pressure-Dependence of Coefficient of Friction

$$\mu = \mu_{max} - \left(\mu_{max} - \mu_{min}\right)exp\left(-a\left|\dot{u}\right|\right)$$

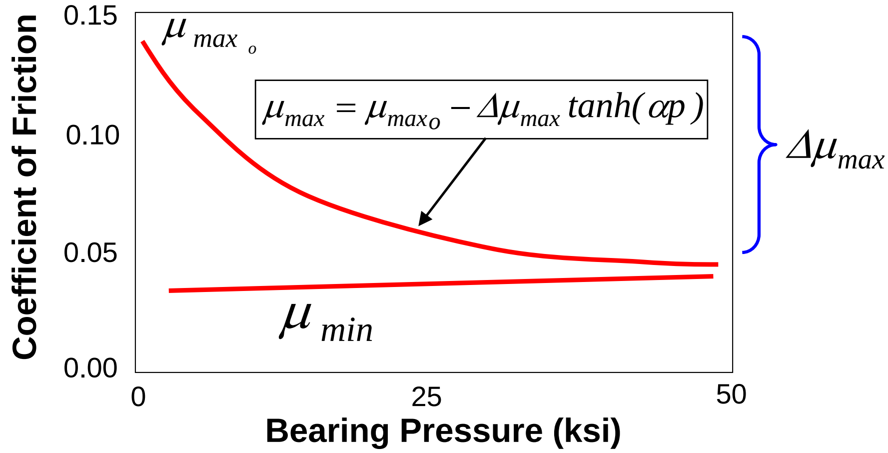


Figure is based on studies of PTFE-based self-lubricating composites used in FPS bearings.

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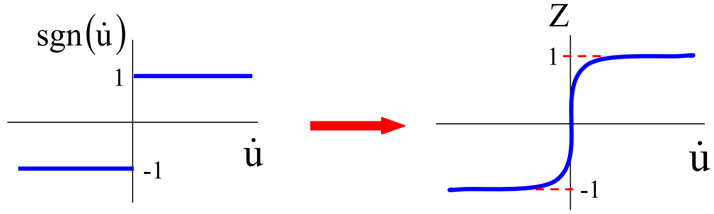
The bearing pressure primarily affects the maximum sliding coefficient of friction (i.e., the sliding coefficient of friction at high velocities). The pressure-dependence of the maximum coefficient of friction may be accounted for by the approximate expression shown.

Refined Model of FPS Bearing Behavior



Viscoplasticity Model

$$Y\dot{Z} + \alpha\,|\dot{u}|\,Z\,|Z|^{\eta-1} + \beta\dot{u}\,|Z|^{\eta} - \gamma\dot{u} = 0$$

Evolutionary Equation

Coefficient of Friction

$$\mu = \mu_{max} - (\mu_{max} - \mu_{min})\,exp(-a|\dot{u}|)$$

$$\boxed{F(t) = \frac{W}{R}u(t) + \mu W\,sgn(\dot{u})} \rightarrow \boxed{F(t) = \frac{W}{R}u(t) + \mu WZ(t)}$$

For more sophisticated analyses, a refined model of the bearings may be utilized in which the evolution of the hysteresis loop is characterized by an evolutionary variable. The path of the evolutionary variable is similar to that of the signum function except that the change in shape near zero velocity is not as abrupt.

Evaluation of Dynamic Behavior of Base-Isolated Structures

- **Isolation Systems are Almost Always Nonlinear and Often Strongly Nonlinear**
- **Equivalent Linear Static Analysis Using Effective Bearing Properties is Commonly Utilized for Preliminary Design**
- **Final Design Should be Performed Using Nonlinear Dynamic Response History Analysis**

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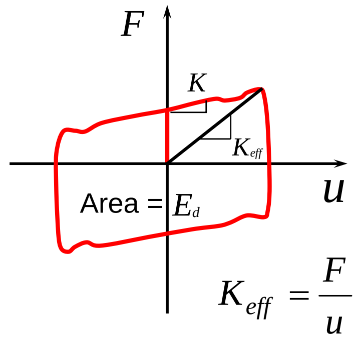
Equivalent Linear Properties of FPS Isolation Bearings



$$F(t) = \frac{W}{R} u(t) + \mu W \, sgn(\dot{u})$$

$$K_{eff} = \frac{F}{u} = \frac{W}{R} + \frac{\mu W}{u}$$

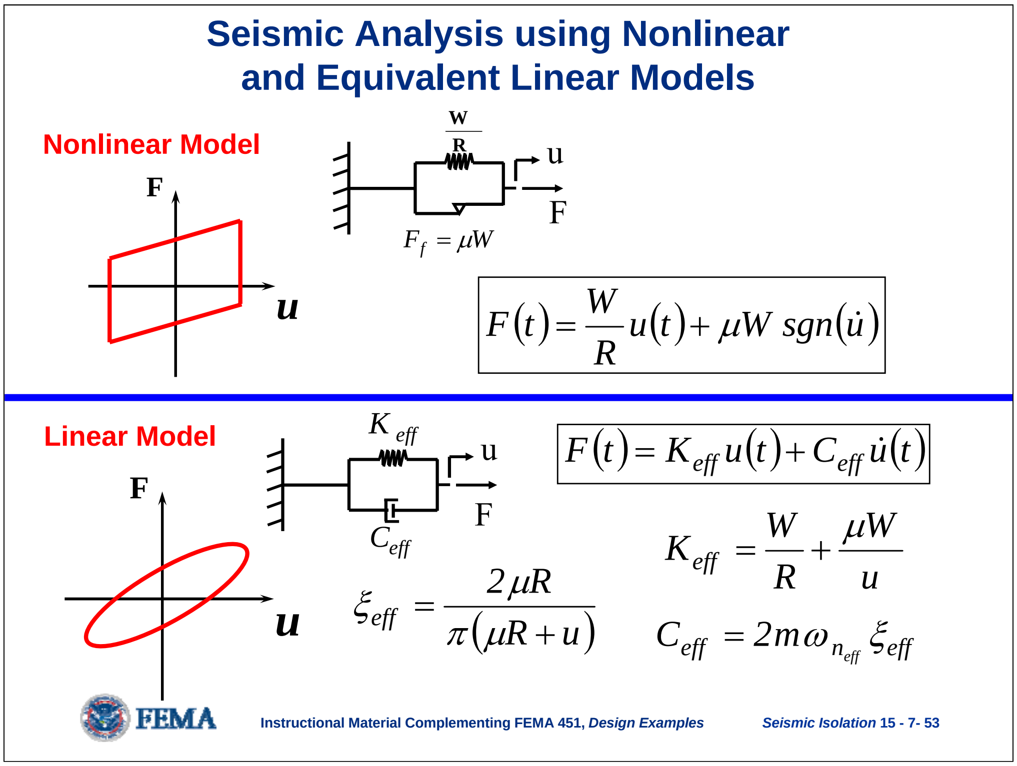
Effective (Secant) Stiffness at Displacement u

$$\xi_{eff} = \frac{E_d}{4\pi E_s} = \frac{4\mu W u}{4\pi\left(0.5 K_{eff} u^2\right)} = \frac{2\mu R}{\pi(\mu R + u)}$$

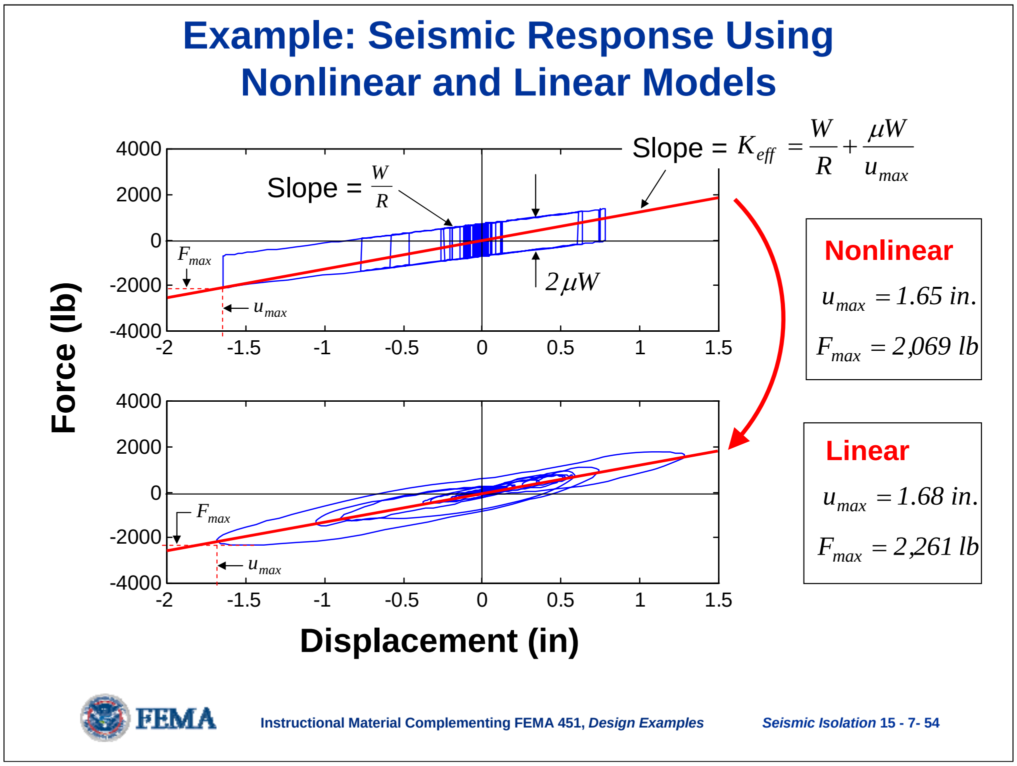
Effective Damping Ratio at Displacement u

Effective linear properties are displacement-dependent. Therefore, design using effective linear properties is an iterative process.

The equivalent linear properties of FPS bearings are the effective stiffness and damping ratio. These quantities may be readily computed from experimental test data. Note that, due to the nonlinear nature of the bearing behavior, the effective bearing properties are displacement-dependent.

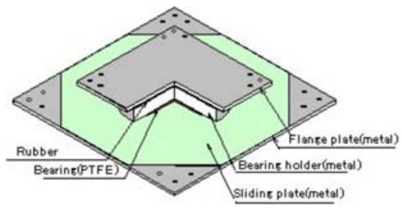


An equivalent linear model can be used to approximate the response of an FPS bearing. The equivalent linear model consists of a linear spring and linear viscous dashpot. The effective properties at a selected displacement are utilized to quantify the stiffness and damping of the model.



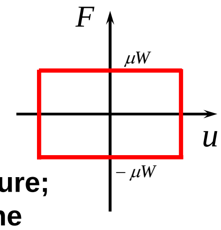
This slide shows results from seismic response analysis of a SDOF isolated structure wherein FPS bearings were utilized. The nonlinear model of the FPS bearings produced the hysteresis loop shown in the top plot. Using the peak displacement from the nonlinear analysis, an equivalent linear model of the FPS bearings was developed. The linear model produced the hysteresis loop shown in the bottom plot. In this case, the peak displacement and bearing force are predicted quite well by the linear model. In general, this is NOT to be expected since the FPS bearing behavior is strongly nonlinear.

Flat Sliding Bearings



For Spherical Bearings:

$$F(t) = \frac{W}{R}u(t) + \mu W\, sgn(\dot{u})$$



- **Flat Bearings:** $R \rightarrow \infty \;\; \therefore \;\; F(t) = \mu W\, sgn(\dot{u})$
- **Bearings do NOT increase natural period of structure; Rather they limit the shear force transferred into the superstructure**
- **Requires supplemental self-centering mechanism to prevent permanent isolation system displacement**
- **Not commonly used in building structures**

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Flat sliding bearings may also be utilized as elements of a base isolation system. In this case, the radius of curvature is infinite and the bearing lateral force is simply equal to the friction force.

Examples of Computer Software for Analysis of Base-Isolated Structures

- **ETABS**
  Linear and nonlinear analysis of buildings
- **SAP2000**
  General purpose linear and nonlinear analysis
- **DRAIN-2D**
  Two-dimensional nonlinear analysis
- **3D-BASIS**
  Analysis of base-isolated buildings

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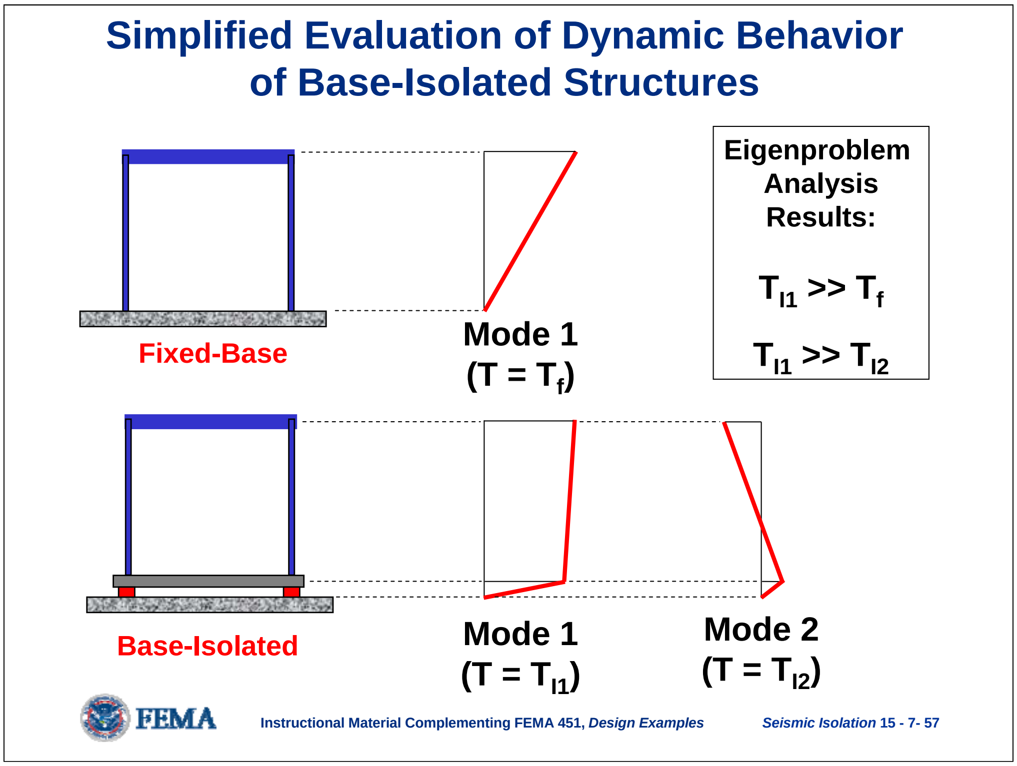
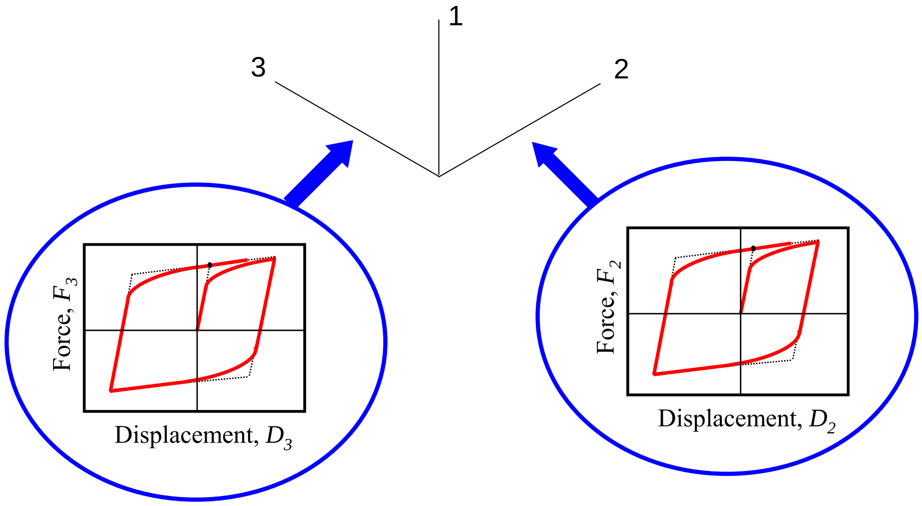


The dynamic behavior of base-isolated structures can be evaluated using a simple one-story building frame and the assumption of linear superstructure and isolation system response. For the fixed-base case, a single mode of vibration exists. For the isolated case, two modes of vibration exist. The first and second modes are said to be the "isolation" and "structural" mode, respectively. The natural period of the isolation mode is much larger than the period of the fixed-base structure and the structural mode of the isolated structure. Furthermore, for seismic loading, the structural mode participation is much less than that of the isolation mode. Thus, as indicated by the mode shape of the isolation mode, most of the deformation in an isolated structure occurs at the isolation level rather than in the superstructure.

Modeling Isolation Bearings Using the SAP2000 NLLINK Element

ISOLATOR1 Property – Biaxial Hysteretic Isolator



The ISOLATOR1 Property of the SAP2000 NLLINK element can be used to model a biaxial hysteretic isolation bearing. This element is well-suited to modeling the behavior of elastomeric bearings.

Coupled Plasticity Equations

$$F_2 = \beta_2 k_2 D_2 + (1-\beta_2)F_{y2}Z_2$$

$$F_3 = \beta_3 k_3 D_3 + (1-\beta_3)F_{y3}Z_3$$

Shear Force Along Each Orthogonal Direction

$$\begin{Bmatrix} \dot{Z}_2 \\ \dot{Z}_3 \end{Bmatrix} = \begin{bmatrix} 1-a_2Z_2^2 & -a_3Z_2Z_3 \\ -a_2Z_2Z_3 & 1-a_3Z_3^2 \end{bmatrix} \begin{Bmatrix} \dfrac{k_2}{F_{y2}}\dot{D}_2 \\ \dfrac{k_3}{F_{y3}}\dot{D}_3 \end{Bmatrix}$$

Coupled Evolutionary Equations

$$a_2 = \begin{cases} 1 & \text{if } \dot{D}_2 Z_2 > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$a_3 = \begin{cases} 1 & \text{if } \dot{D}_3 Z_3 > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$\sqrt{Z_2^2 + Z_3^2} \le 1$$

Range of Evolutionary Variables

$$\sqrt{Z_2^2 + Z_3^2} = 1$$

Defines Yield Surface

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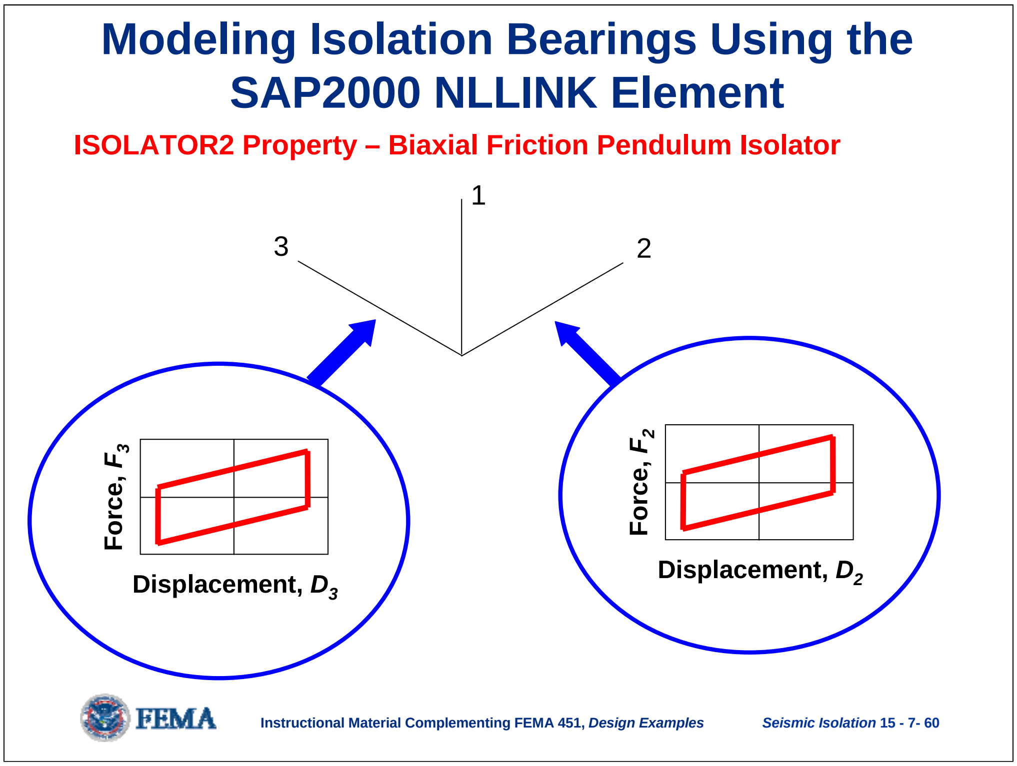
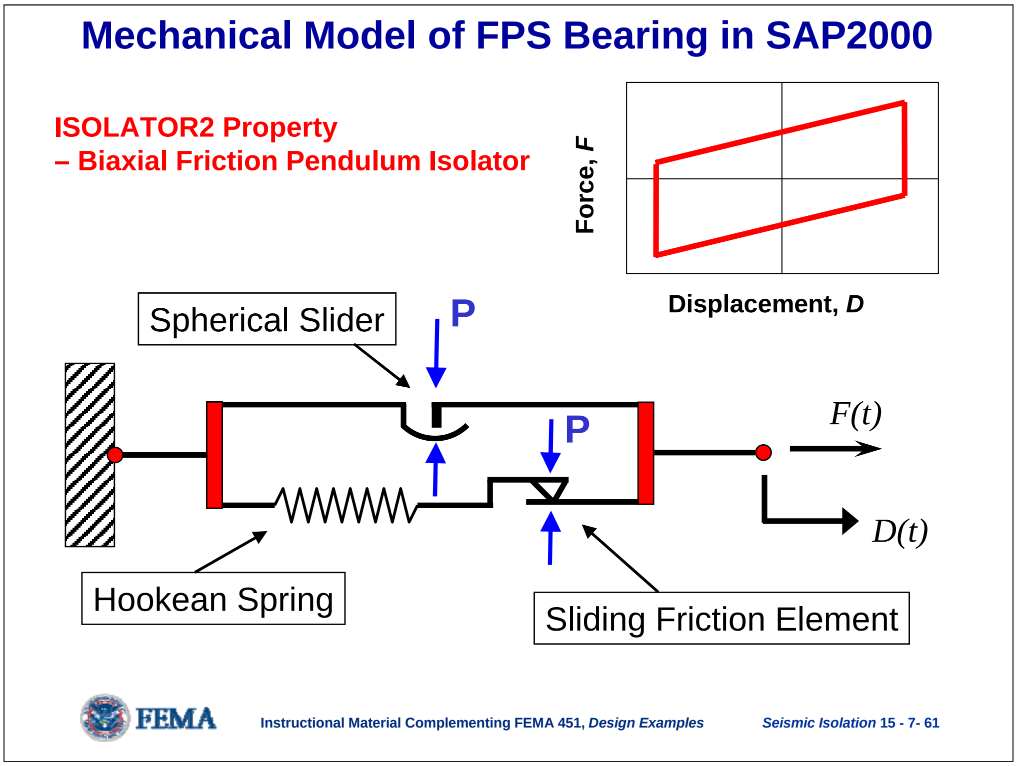
If only one shear degree of freedom is considered, the above equations reduce to the uniaxial plasticity behavior of the PLASTIC1 property with an exponent value of 2.



The ISOLATOR2 Property of the SAP2000 NLLINK element can be used to model a biaxial Friction Pendulum System isolation bearing.

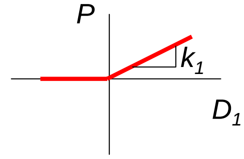


The mechanical model of the ISOLATOR2 Element consists of a linear spring in series with a friction element, both of which are in parallel with a slider element. The linear spring provides the initial stiffness that occurs prior to slippage of the bearing. Once slippage occurs, the friction element slides which in turn produces deformation in the slider element.

Forces in Biaxial FPS Isolator

$$F_1 = P = \begin{cases} k_1 D_1 & \text{if } D_1 < 0 \\ 0 & \text{otherwise} \end{cases}$$

Axial Force:
+ = Comp.
- = Tension



$$\left.\begin{aligned} F_2 &= \frac{P}{R_2} D_2 + P\mu_2 Z_2 \\ F_3 &= \frac{P}{R_3} D_3 + P\mu_3 Z_3 \end{aligned}\right\} \text{ Shear Force Along Each Orthogonal Direction}$$

For FPS Bearing, $R_2 = R_3$

$$\left.\begin{aligned} \mu_2 &= \mu_{max\,2} - (\mu_{max\,2} - \mu_{min\,2})e^{-rv} \\ \mu_3 &= \mu_{max\,3} - (\mu_{max\,3} - \mu_{min\,3})e^{-rv} \end{aligned}\right\} \text{ Friction Coefficients}$$

$$v = \sqrt{\dot{D}_2^2 + \dot{D}_3^2}$$

Resultant Velocity

$$r = \frac{r_2 \dot{D}_2^2 + r_3 \dot{D}_3^2}{v^2}$$

Effective Inverse Velocity

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No annotation is provided for this slide.

Forces in Biaxial FPS Isolator

$$\begin{Bmatrix} \dot{Z}_2 \\ \dot{Z}_3 \end{Bmatrix} = \begin{bmatrix} 1 - a_2 Z_2^2 & -a_3 Z_2 Z_3 \\ -a_2 Z_2 Z_3 & 1 - a_3 Z_3^2 \end{bmatrix} \begin{Bmatrix} \dfrac{k_2}{P\mu_2}\dot{D}_2 \\ \dfrac{k_3}{P\mu_3}\dot{D}_3 \end{Bmatrix}$$

Coupled Evolutionary Equations

$$a_2 = \begin{cases} 1 & \text{if } \dot{D}_2 Z_2 > 0 \\ 0 & \text{otherwise} \end{cases} \qquad \sqrt{Z_2^2 + Z_3^2} \le 1$$

Range of Evolutionary Variables

$$a_3 = \begin{cases} 1 & \text{if } \dot{D}_3 Z_3 > 0 \\ 0 & \text{otherwise} \end{cases} \qquad \sqrt{Z_2^2 + Z_3^2} = 1$$

Defines Yield Surface

$k_2, \; k_3$ *Elastic Shear Stiffnesses (stiffness prior to sliding)*

Note: Flat Bearings: Set R = 0 for both directions
(restoring forces will be set equal to zero).
Cylindrical Bearings: Set R = 0 for one direction.

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If only one nonlinear shear degree of freedom is considered, the above equations reduce to unidirectional FPS bearing behavior with either linear or zero restoring force along the orthogonal direction.

Historical Development of Code Provisions for Base Isolated Structures

- Late 1980's: BSB (Building Safety Board of California) "An Acceptable Method for Design and Review of Hospital Buildings Utilizing Base Isolation"
- 1986 SEAONC "Tentative Seismic Isolation Design Requirements"
  - Yellow book [emphasized equivalent lateral force (static) design]
- 1990 SEAOC "Recommended Lateral Force Requirements and Commentary"
  - Blue Book
  - Appendix 1L: "Tentative General Requirements for the Design and Construction of Seismic-Isolated Structures"
- 1991 and 1994 Uniform Building Code
  - Appendix entitled: "Earthquake Regulations for Seismic-Isolated Structures"
  - Nearly identical to 1990 SEAOC Blue Book
- 1994 NERHP Recommended Provisions for Seismic Regulations for New Buildings (FEMA 222A – Provisions; FEMA 223A - Commentary)
  - Section 2.6: Provisions for Seismically Isolated Structures
  - Based on 1994 UBC but modified for strength design and national applicability

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Recall that the first isolated building was constructed in 1985 (Foothill Communities Law and Justice Center, Rancho Cucamonga, CA), well before established code provisions were in place.

Historical Development of Code Provisions for Base Isolated Structures

- **1996 SEAOC "Recommended Lateral Force Requirements and Commentary"**
  - Chapter 1, Sections 150 to 161 (chapters/sections parallel those of 1994 UBC)
- **1997 Uniform Building Code**
  - Appendix entitled: "Earthquake Regulations for Seismic-Isolated Structures"
  - Essentially the same as 1991 and 1994 UBC
- **1997 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures (FEMA 302 – Provisions; FEMA 303 - Commentary)**
  - Chapter 13: Seismically Isolated Structures Design Requirements
  - Based on 1997 UBC (almost identical)
- **1997 NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA 273 – Guidelines; FEMA 274 - Commentary)**
  - Chapter 9: Seismic Isolation and Energy Dissipation
  - Introduces Nonlinear Static (pushover) Analysis Procedure
  - Isolation system design is similar to that for new buildings but superstructure design considers differences between new and existing structures

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Historical Development of Code Provisions for Base Isolated Structures

- **1999 SEAOC "Recommended Lateral Force Requirements and Commentary"**
  - Chapter 1, Sections 150 to 161 (chapters/sections parallel those of 1997 UBC)

- **2000 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures (FEMA 368 – Provisions; FEMA 369 - Commentary)**
  - Chapter 13: Seismically Isolated Structures Design Requirements

- **2000 Prestandard and Commentary for the Seismic Rehabilitation of Buildings (FEMA 356)**
  - Chapter 9: Seismic Isolation and Energy Dissipation

- **2000 International Building Code (IBC)**
  - Section 1623: Seismically Isolated Structures
  - Based on 1997 NEHRP Provisions
  - Similar to FEMA 356 since same key persons prepared documents

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No annotation is provided for this slide.

General Philosophy of Building Code Provisions

- No specific isolation systems are described
- All isolation systems must:
  - Remain stable at the required displacement
  - Provide increasing resistance with increasing displacement
  - Have non-degrading properties under repeated cyclic loading
  - Have quantifiable engineering parameters

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Design Objectives of 2000 NEHRP and 2000 IBC Base Isolation Provisions

- **Minor and Moderate Earthquakes**
  - **No damage to structural elements**
  - **No damage to nonstructural components**
  - **No damage to building contents**
- **Major Earthquakes**
  - **No failure of isolation system**
  - **No significant damage to structural elements**
  - **No extensive damage to nonstructural components**
  - **No major disruption to facility function**
  - **Life-Safety**

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2000 NEHRP and 2000 IBC Base Isolation Provisions

General Design Approach

EQ for Superstructure Design

Design Earthquake
10%/50 yr = 475-yr return period
- Loads reduced by up to a factor of 2 to allow for limited Inelastic response; a similar fixed-base structure would be designed for loads reduced by a factor of up to 8

EQ for Isolation System Design (and testing)

Maximum Considered Earthquake
2%/50 yr = 2,500-yr return period
- No force reduction permitted for design of isolation system

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To meet the objectives of the 2000 NEHRP and IBC Provisions, the general design approach is as described in this slide. Note that the design earthquake is taken as 2/3 of the maximum considered earthquake.

Analysis Procedures of 2000 NEHRP and 2000 IBC Base Isolation Provisions

- **Equivalent Lateral Response Procedure**
  - **Applicable for final design under limited circumstances**
  - **Provides lower bound limits on isolation system displacement and superstructure forces**
  - **Useful for preliminary design**

Presented Herein

- **Dynamic Lateral Response Procedure**
  - **May be used for design of any isolated structure**
  - **Must be used if structure is geometrically complex or very flexible**
  - **Two procedures:**
    - **Response Spectrum Analysis (linear)**
    - **Response-History Analysis (linear or nonlinear)**

FEMA

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Isolation System Displacement (Translation Only)

Design Displacement

Design Spectral Acceleration at One-Second Period (g)

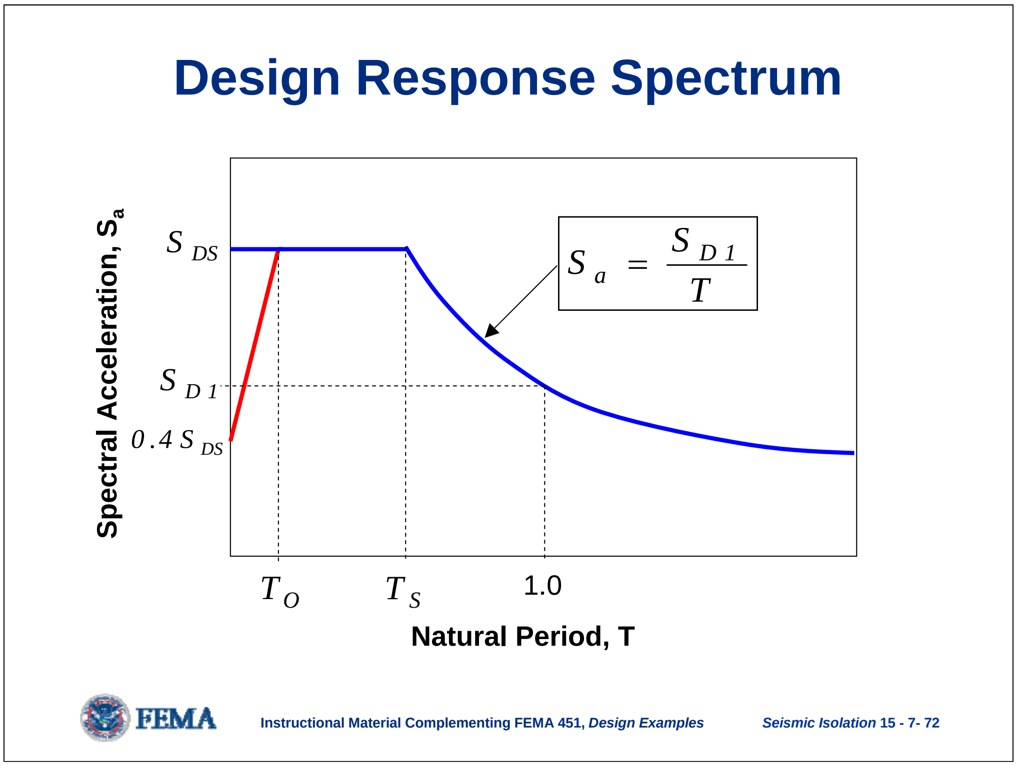
$$D_D = \left(\frac{g}{4\pi^2}\right)\frac{S_{D1}T_D}{B_D}$$

Effective Period of Isolated Structure at Design Displacement

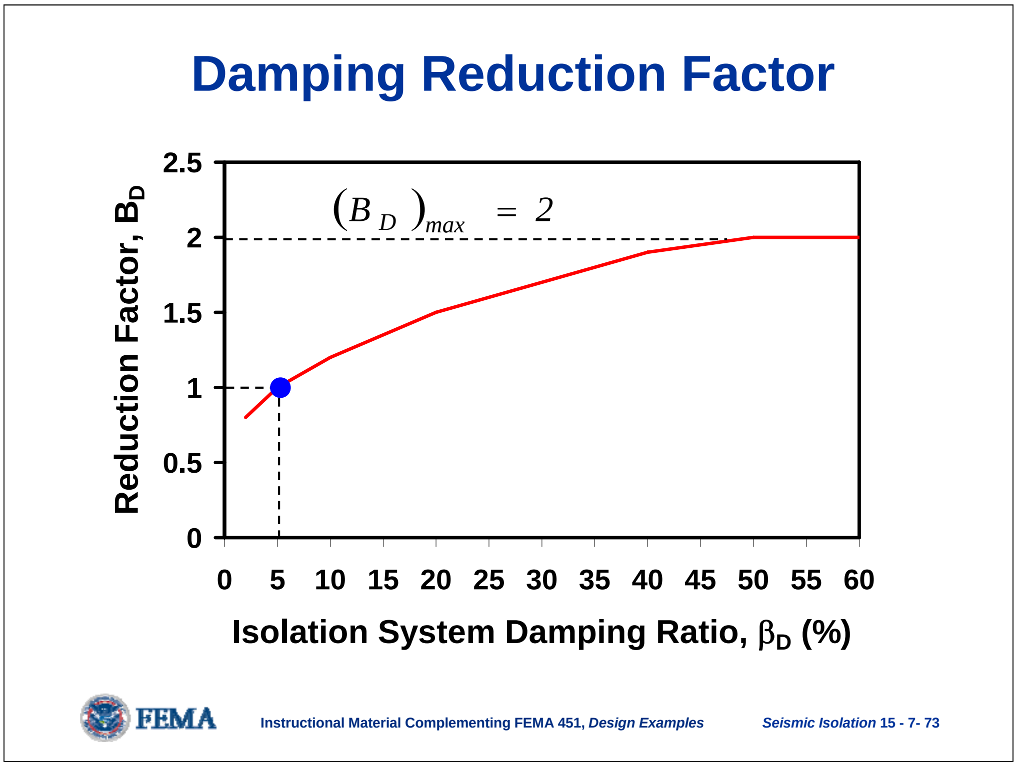
Damping Reduction Factor for Isolation System at Design Displacement

Design is evaluated at two levels:
- Design Earthquake: 10% / 50 yr = 475-yr return period
- Maximum Considered Earthquake: 2% / 50 yr = 2,500-yr return period

The design displacement of the isolation system approximates the peak displacement of a SDOF, linear, elastic system. The superstructure is assumed to be rigid and thus the natural period is controlled by the flexibility of the isolation system. The damping in the isolation system reduces the peak displacement demand. The design displacement occurs at the Center of Rigidity (CR) of the isolation system.



The red line at short periods is used for dynamic response spectrum analysis whereas the blue line at short periods is used for equivalent linear static analysis.



As expected, the damping reduction factor (which appears in the denominator of the design displacement equation) increases with increasing isolation system damping ratio. Note that the reduction factor is anchored at a value of unity which corresponds to an isolation system damping ratio of 5%. The damping reduction factor is limited to a value of 2 (i.e., the design displacement may be reduced by up to 50% of the nominal value associated with 5% damping).

Effective Isolation Period

Effective Period

$$T_D = 2\pi \sqrt{\frac{W}{k_{D\,min}\, g}}$$

Total Seismic Dead Load Weight

Minimum Effective Stiffness of Isolation System at Design Displacement

Minimum stiffness used so as to produce largest period and thus most conservative design displacement.

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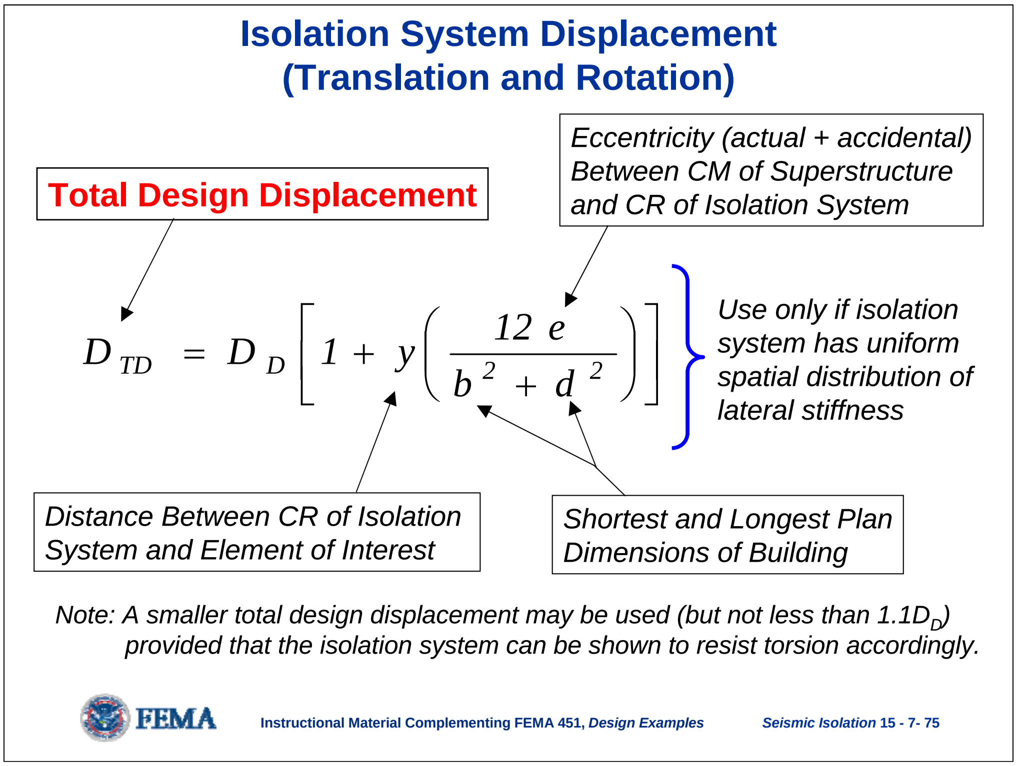
The effective period is given by the expression for the natural period of a SDOF, linear, elastic system. The superstructure is assumed to be rigid and thus the natural period is controlled by the flexibility of the isolation system. For conservative design, the minimum effective stiffness is utilized to compute the effective natural period.



The total design displacement of the isolation system includes contributions from both translation and rotation. Rotation is caused by a torsional response of the isolation system due to an offset of the Center of Rigidity (CR) of the isolation system and the Center of Mass (CM) of the superstructure. The inertial forces pass through the CM while the resultant bearing resisting force passes through the CR. If an offset in the CR and CM is present, the two forces are not coincident and torsional (rotation) response is induced. The rotation increases the isolation system displacements at the corners of the buildings. This increased displacement at a corner of the building is the Total Design Displacement.

Note that a smaller total design displacement may be utilized if it can be shown that the isolation system can resist torsion. For example, for an FPS isolation system, torsional response is virtually eliminated and thus the minimum value of 110% of D_D would apply.

Base Shear Force

Isolation System and Elements Below Isolation System

$$V_b = k_{D\ max} D_D$$

No Force Reduction; Therefore Elastic Response Below Isolation System

Maximum Effective Isolation System Stiffness

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For conservative design, the maximum effective stiffness is used to compute the shear force at and below the isolation system. Also, as explained previously, for conservative design the design displacement is based on the minimum effective stiffness. Thus, the maximum and minimum stiffnesses are used in such a manner that the worst case is considered for both displacements and shear forces.

Shear Force Above Isolation System

Structural Elements Above Isolation System

$$V_S = \frac{k_{D\,max}\, D_D}{R_I}$$

Response Modification Factor for Isolated Superstructure

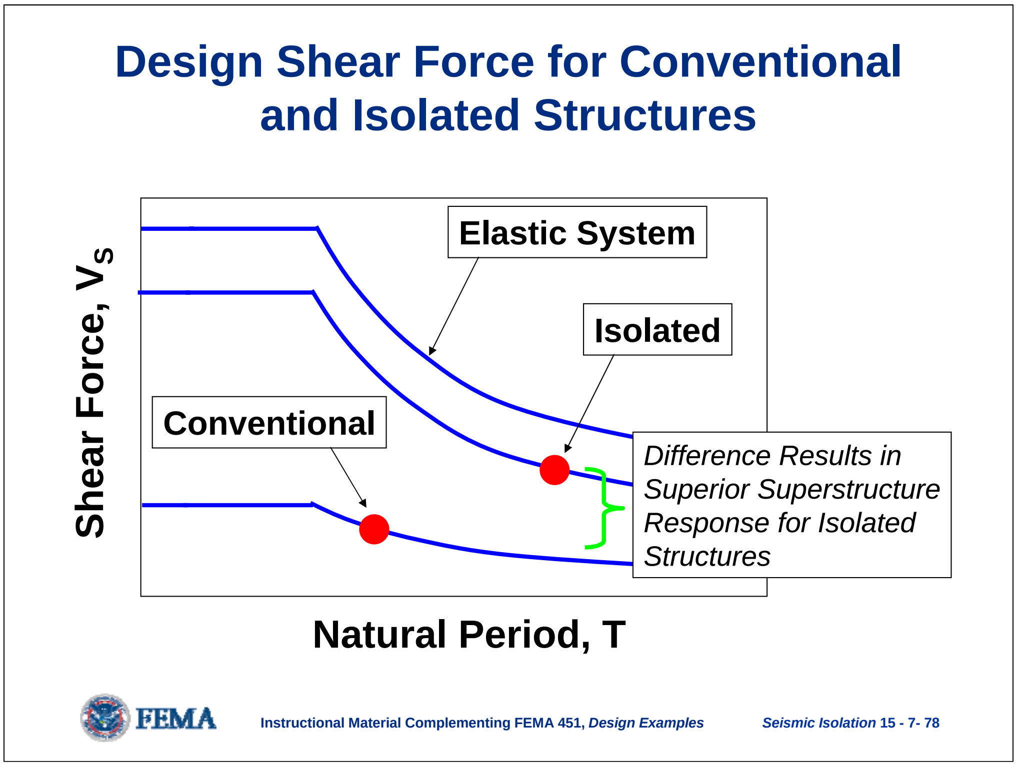
$$R_I = \frac{3}{8} R = \frac{R}{2.67} \leq 2$$

Ensures essentially elastic superstructure response

Minimum Values of V_S:

- Base shear force for design of conventional structure of fixed-base period T_D
- Shear force for wind design.
- 1.5 times shear force that activates isolation system.

With the overstrength and redundancy in the superstructure, a small value of R_I ensures essentially elastic superstructure response. The last criteria shown for the minimum value of the base shear ensures that the superstructure does not respond inelastically before the isolation system has been activated (i.e., displaced significantly). Examples of the “shear force that activates the isolation system” would be the yield force of an elastomeric bearing system or the static friction force of a sliding system.



Due to the low value of the strength reduction factor for isolated structures, the design shear force for isolated structures is generally larger than that for conventional structures. The larger design shear force results in superior superstructure response for isolated structures.

Example: Evaluation of Design Shear Force

Base Shear Coefficient

$$BSC_I = \frac{V_S}{W} = \frac{k_{D\,max} D_D}{W R_I} = \frac{S_{D1}}{B_D R_I T_D}$$ *Isolated Structure*

$$BSC_C = \frac{V_S}{W} = C_S = \frac{S_{D1}}{T(R/I)}$$ *Conventional Structure Having Period of One-Second or More*

$$\frac{BSC_I}{BSC_C} = \frac{T(R/I)}{B_D R_I T_D}$$

Example:

- Fire Station (I = 1.5)
- Conventional: Special steel moment frame (R = 8.5) and T = 1.0 sec
- Isolated: T_D = 2.0 sec, damping ratio = 10% (B_D = 1.2), R_I = 2

Result: $$\frac{BSC_I}{BSC_C} = 1.18$$

Isolating structure results in 18% *increase* in shear force for design of superstructure

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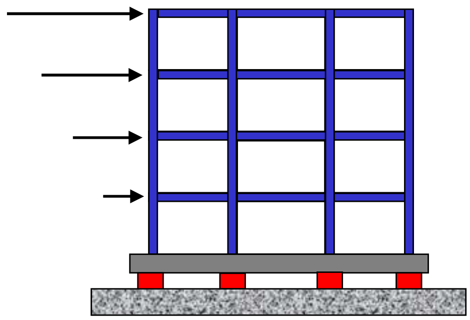
This example illustrates the difference between the base shear coefficient for a conventional and base-isolated structure.

Distribution of Shear Force

$$F_x = \frac{V_S w_x h_x}{\sum_{i=1}^{n} w_i h_i}$$

Standard Inverted Triangular Distribution of Base Shear

Lateral Force at Level x of the Superstructure



The base shear force is distributed to the superstructure in the form of an inverted triangle (assuming uniform mass distribution and story heights). For an isolated structure, the actual pattern of lateral load is expected to be relatively uniform since the superstructure is expected to behave essentially as a rigid body. The triangular distribution is used to capture possible higher-mode effects due to nonlinear behavior of the isolation system (e.g., due to friction in sliding bearings or yielding of lead plugs in lead-rubber bearings). Furthermore, studies have shown that the triangular force distribution provides a conservative estimate of the distributions obtained from detailed nonlinear analyses.

Interstory Drift Limit

Displacement at Level x of Superstructure

Deflection Amplification Factor

Displacement at Level x of Superstructure Based on Elastic Analysis

$$\delta_x = \frac{C_d \delta_{xe}}{I}$$

Occupancy Importance Factor

Note: For Isolated Structures, C_d is replaced by R_I.

Interstory Drift of Story x

$$\Delta_x \leq 0.015\ h_{sx}$$

Height of Story x

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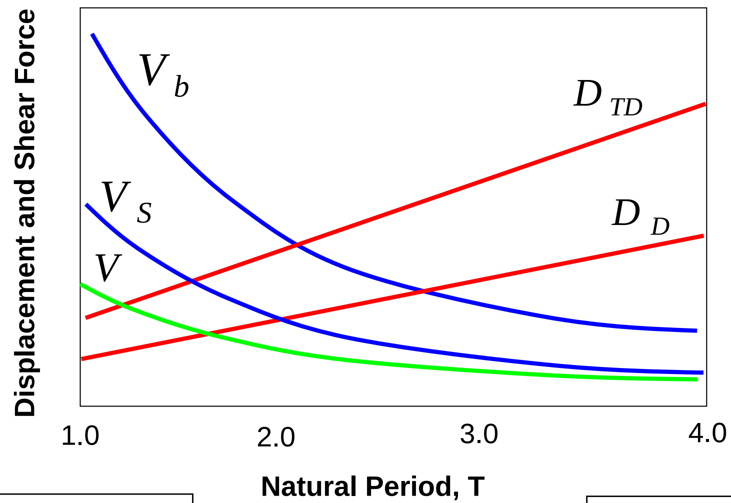
Displacement and Shear Force Design Spectrum



$$V_b = k_{D\,max} D_D$$

$$V_S = \frac{k_{D\,max} D_D}{R_I}$$

$$V = C_S W$$

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As the natural period of the isolated structure increases, the design displacements increase linearly. At all periods, the total design displacement is a constant multiple of the design displacement. As the natural period of the isolated structure increases beyond one-second, the design shear forces for both isolated and conventional structures are inversely proportional to the natural period. At all periods, the base shear force in an isolated structure (force at and below isolation system) is a constant multiple of the superstructure shear force (force above isolation system).

Required Tests of Isolation System

Prototype Tests on Two Full-Size Specimens of Each Predominant Type of Isolation Bearing

- **Check Wind Effects**
  - **20 fully reversed cycles at force corresponding to wind design force**
- **Establish Displacement-Dependent Effective Stiffness and Damping**
  - **3 fully reversed cycles at $0.25D_D$**
  - **3 fully reversed cycles at $0.5D_D$**
  - **3 fully reversed cycles at $1.0D_D$**
  - **3 fully reversed cycles at $1.0D_M$**
  - **3 fully reversed cycles at $1.0\ D_{TM}$**
- **Check Stability**
  - **Maximum and minimum vertical load at $1.0\ D_{TM}$**
- **Check Durability**
  - **$30S_{D1}B_D/S_{DS}$, but not less than 10, fully reversed cycles at $1.0\ D_{TD}$**

For cyclic tests, bearings must carry specified vertical (dead and live) loads

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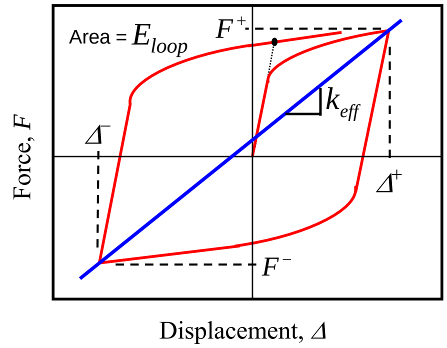
The stability tests check for buckling (maximum vertical load) and uplift restraint (minimum vertical load).

Effective Linear Properties of Isolation Bearing from Cyclic Testing



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

Effective Stiffness of Isolation Bearing

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

Equivalent Viscous Damping Ratio of Isolation Bearing

Effective properties determined for each cycle of loading

For purposes of final design, the effective linear properties of the isolation bearings are obtained/verified from the required experimental tests.

Effective Linear Properties of Isolation System from Cyclic Testing

Absolute Maximum Force at Positive D_D over 3 Cycles of Motion at $1.0D_D$

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

Maximum Effective Stiffness of Isolation System

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

Minimum Effective Stiffness of Isolation System

Use smallest value from cyclic tests

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

Equivalent Viscous Damping Ratio of Isolation System

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The effective linear properties of the isolation system are obtained from the experimental testing results of individual isolation bearings. The summations extend over all isolation bearings. The effective isolation system properties can be used within either a linear static (equivalent lateral force) or linear dynamic (response spectrum) analysis. For preliminary design, the effective properties are estimated and either equivalent lateral load analysis or dynamic response spectrum analysis is performed. For final design, dynamic response spectrum analysis is usually performed using the effective linear properties from the required experimental tests. Note that, while both the equivalent lateral force and dynamic response spectrum methods are considered to be linear methods, they both make use of effective linear bearing properties that are displacement-dependent. Thus, the methods implicitly account for the nonlinear properties of the isolation bearings.

Additional Issues to Consider

- Buckling and stability of elastomeric bearings
- High-strain stiffening of elastomeric bearings
- Longevity (time-dependence) of bearing materials
  (Property Modification Factors to appear in 2003 NEHRP Provisions)
- Displacement capacity of non-structural components that cross isolation plane
- Displacement capacity of building moat
- Second-order (P-Δ) effects on framing above and below isolation system

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Example Design of Seismic Isolation System Using 2000 NEHRP Provisions

Seismically Isolated Structures by Charles A. Kircher
Chapter 11 of *Guide to the Application of the 2000 NEHRP Provisions;* *Note: The Guide is in final editing. Chapter 11 is in the handouts.*

Structure and Isolation System
- “Hypothetical” Emergency Operations Center, San Fran., CA
- Three-Story Steel Braced-Frame with Penthouse
- High-Damping Elastomeric Bearings

Design Topics Presented:
- Determination of seismic design parameters
- Preliminary design of superstructure and isolation system
- Dynamic analysis of isolated structure
- Specification of isolation system design and testing criteria

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