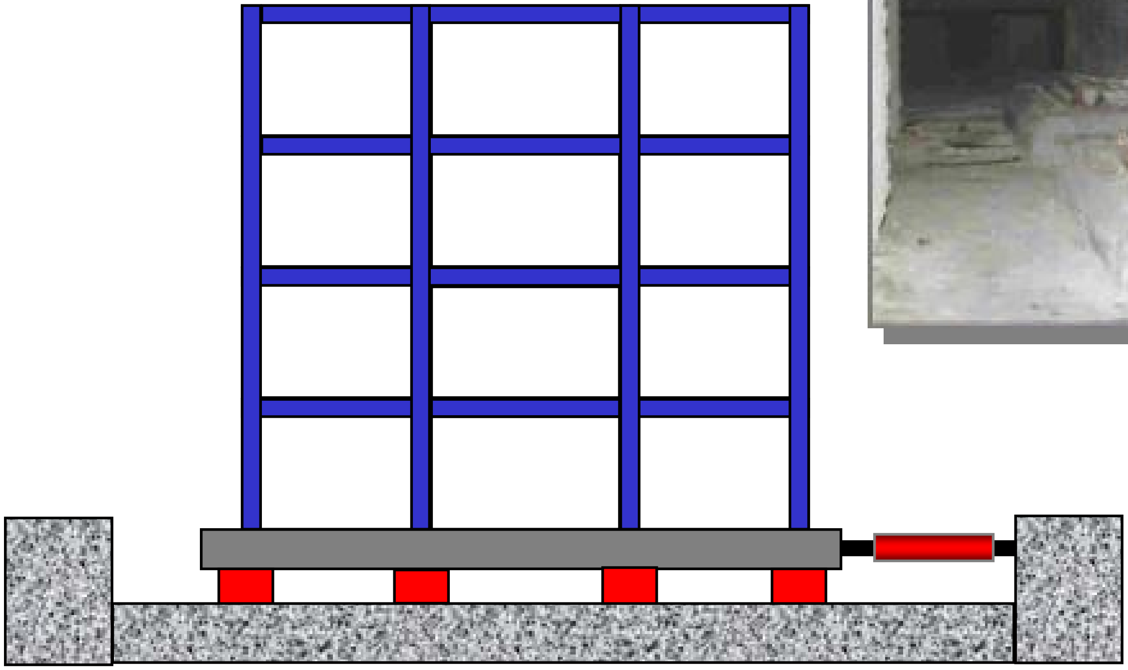
SEISMIC PROTECTIVE SYSTEMS: SEISMIC ISOLATION

Developed by:

Michael D. Symans, PhD

Rensselaer Polytechnic Institute



Major Objectives

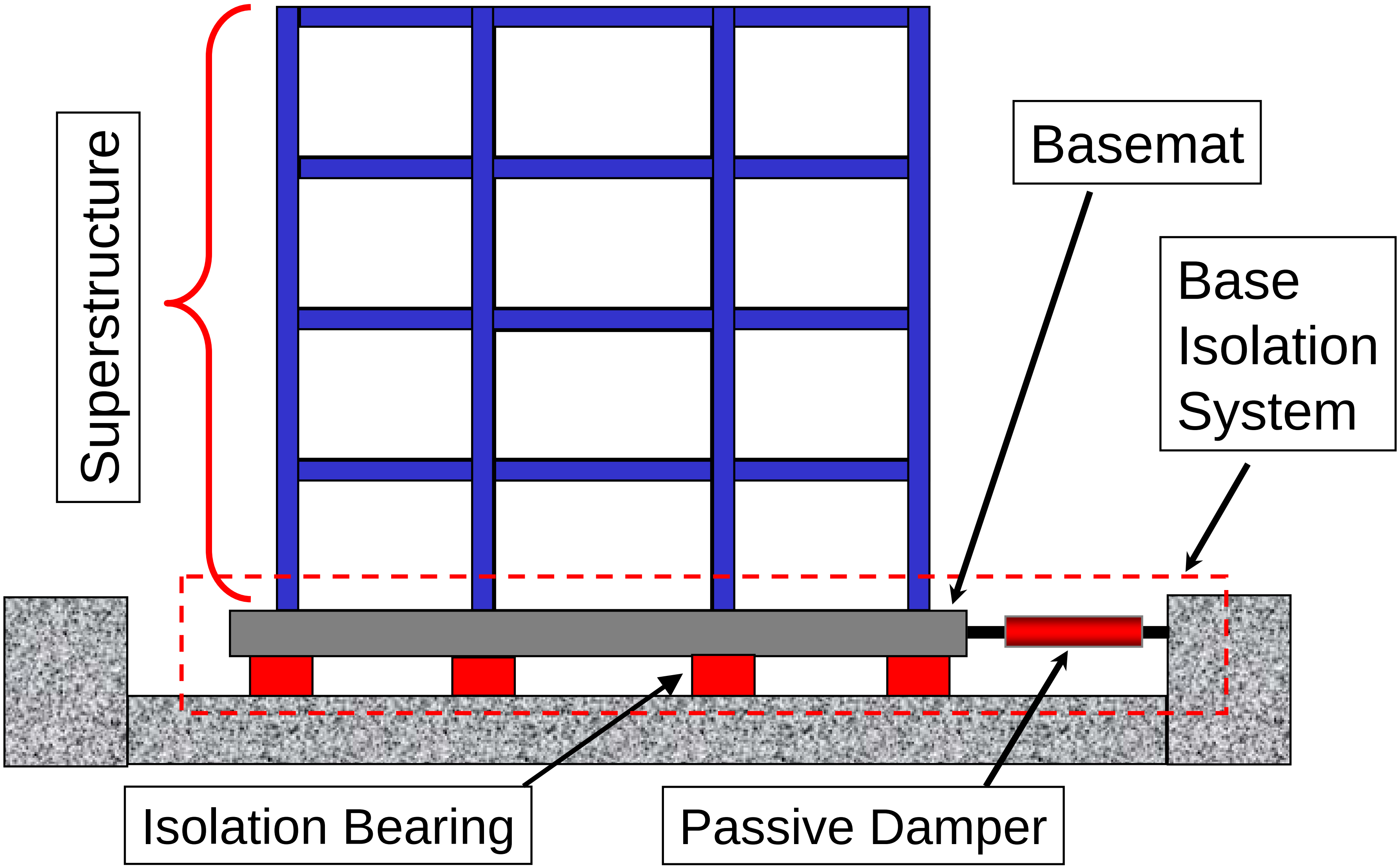
- Illustrate why use of seismic isolation systems may be beneficial
- Provide overview of types of seismic isolation systems available
- Describe behavior, modeling, and analysis of structures with seismic isolation systems
- Review building code requirements

Outline

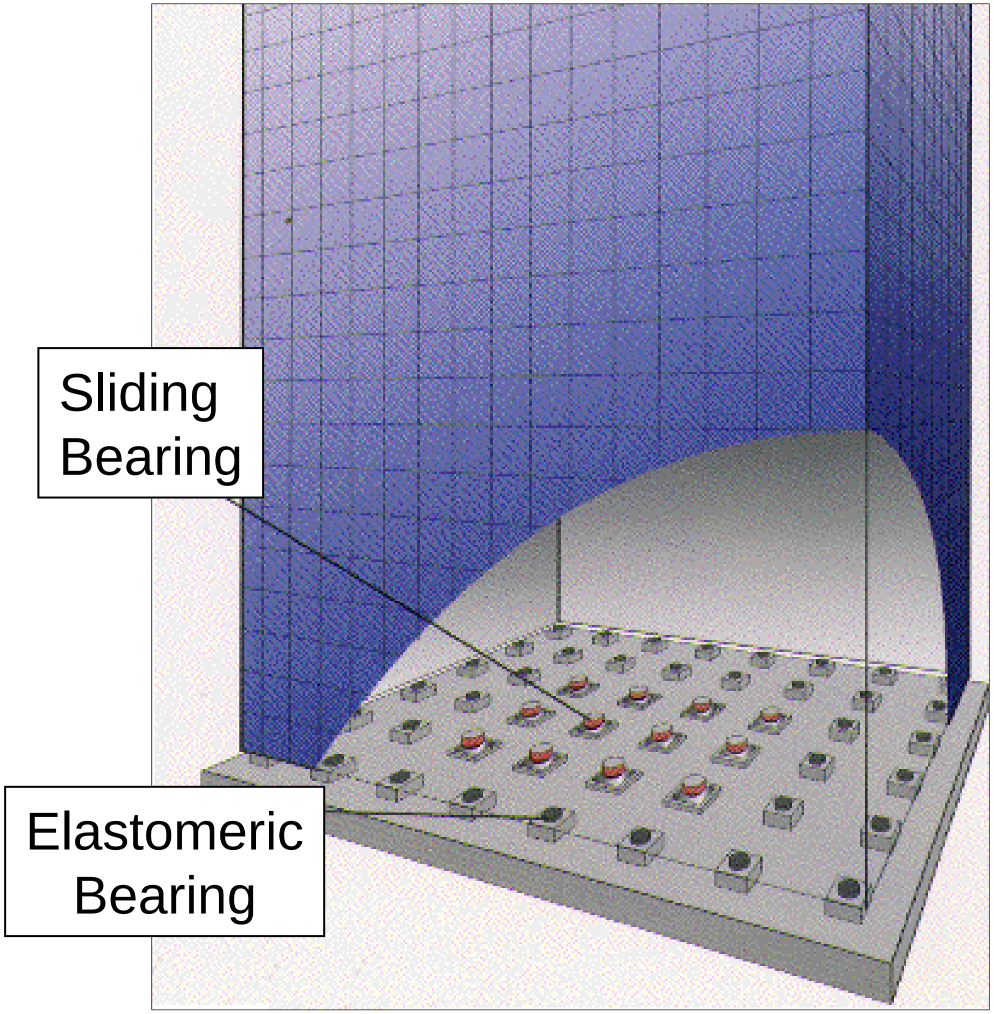
Seismic Base Isolation

– 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

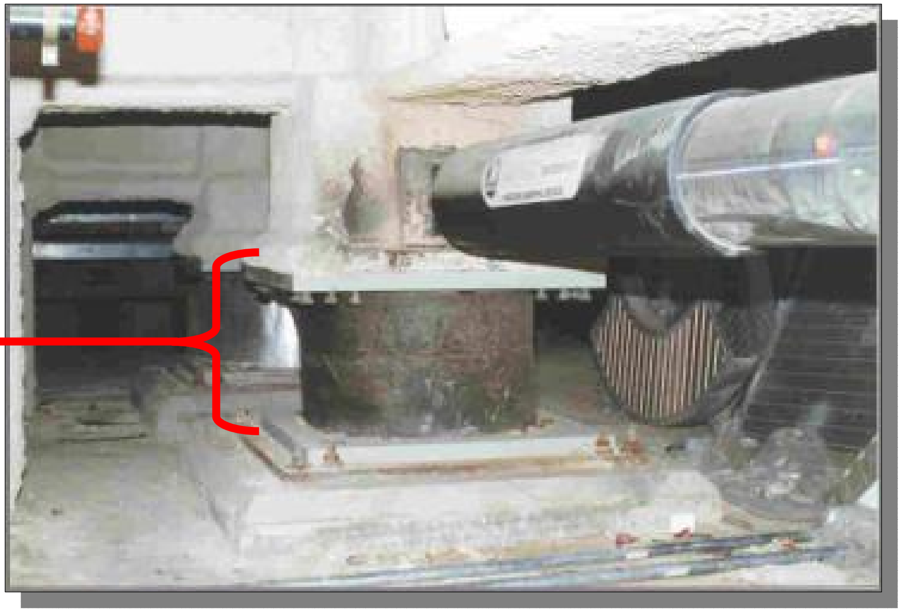
Configuration of Building Structure with Base Isolation System

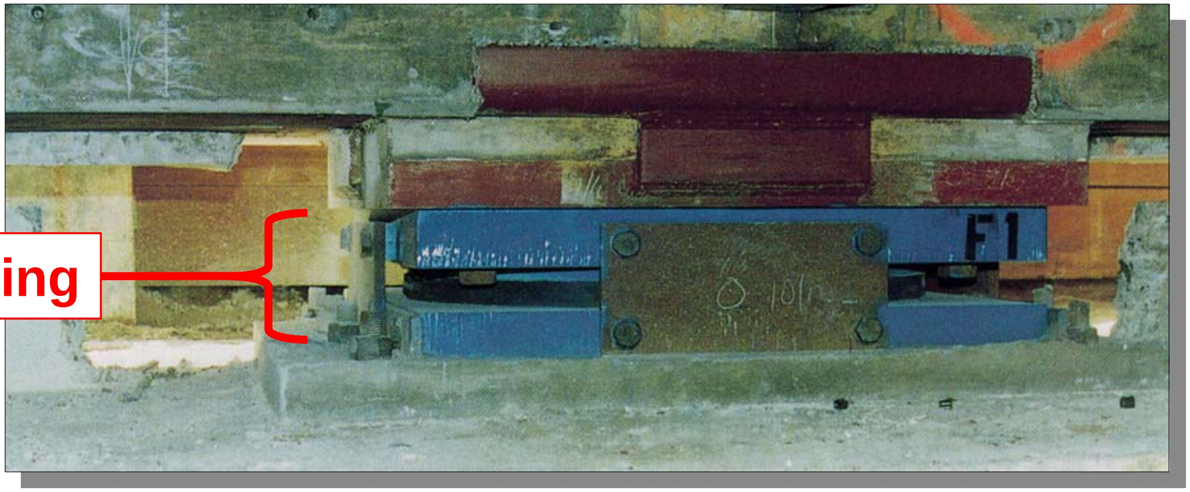


Three-Dimensional View of Building Structure with Base Isolation System

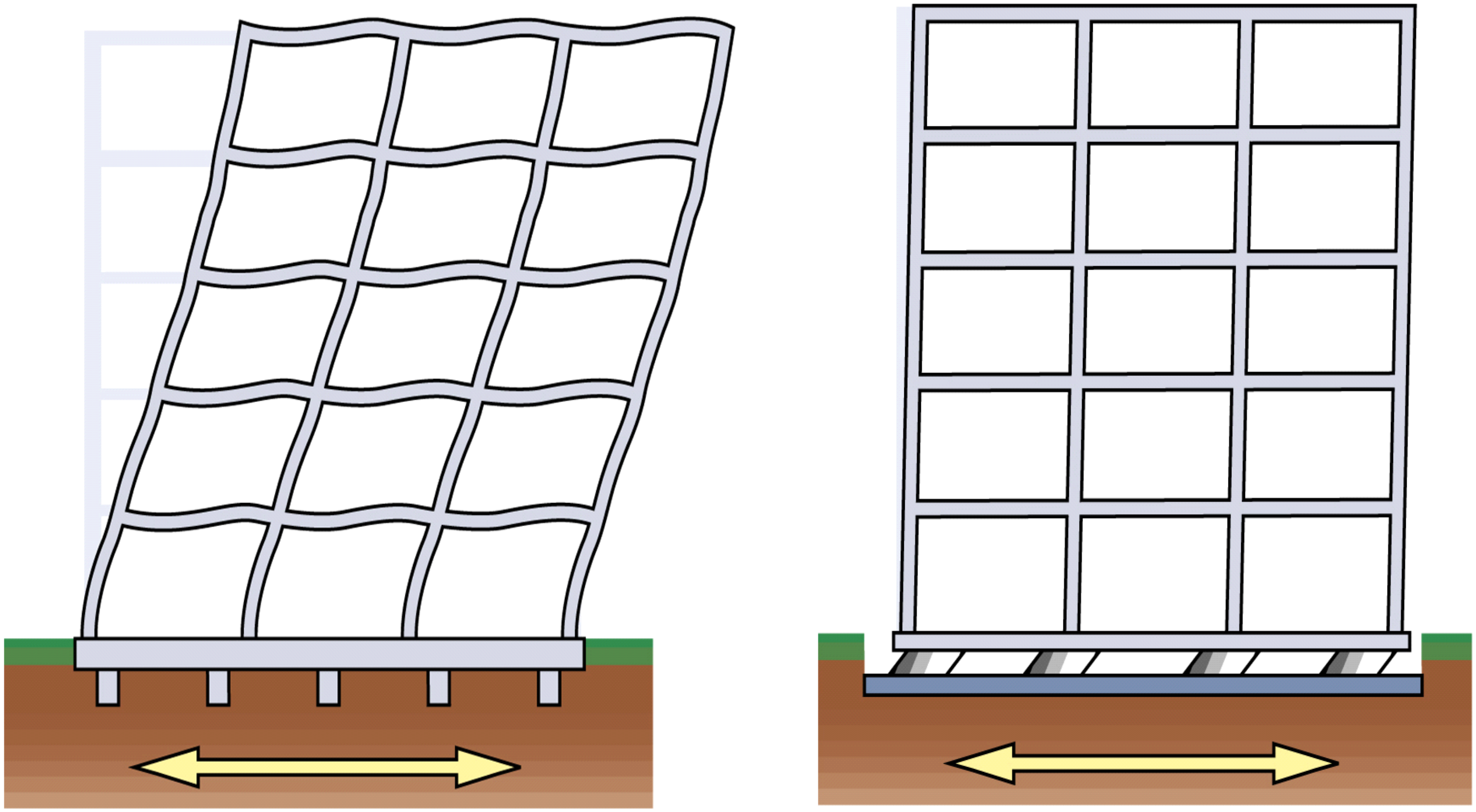


Installed Seismic Isolation Bearings





Behavior of Building Structure with Base Isolation System



Conventional Structure

Base-Isolated Structure

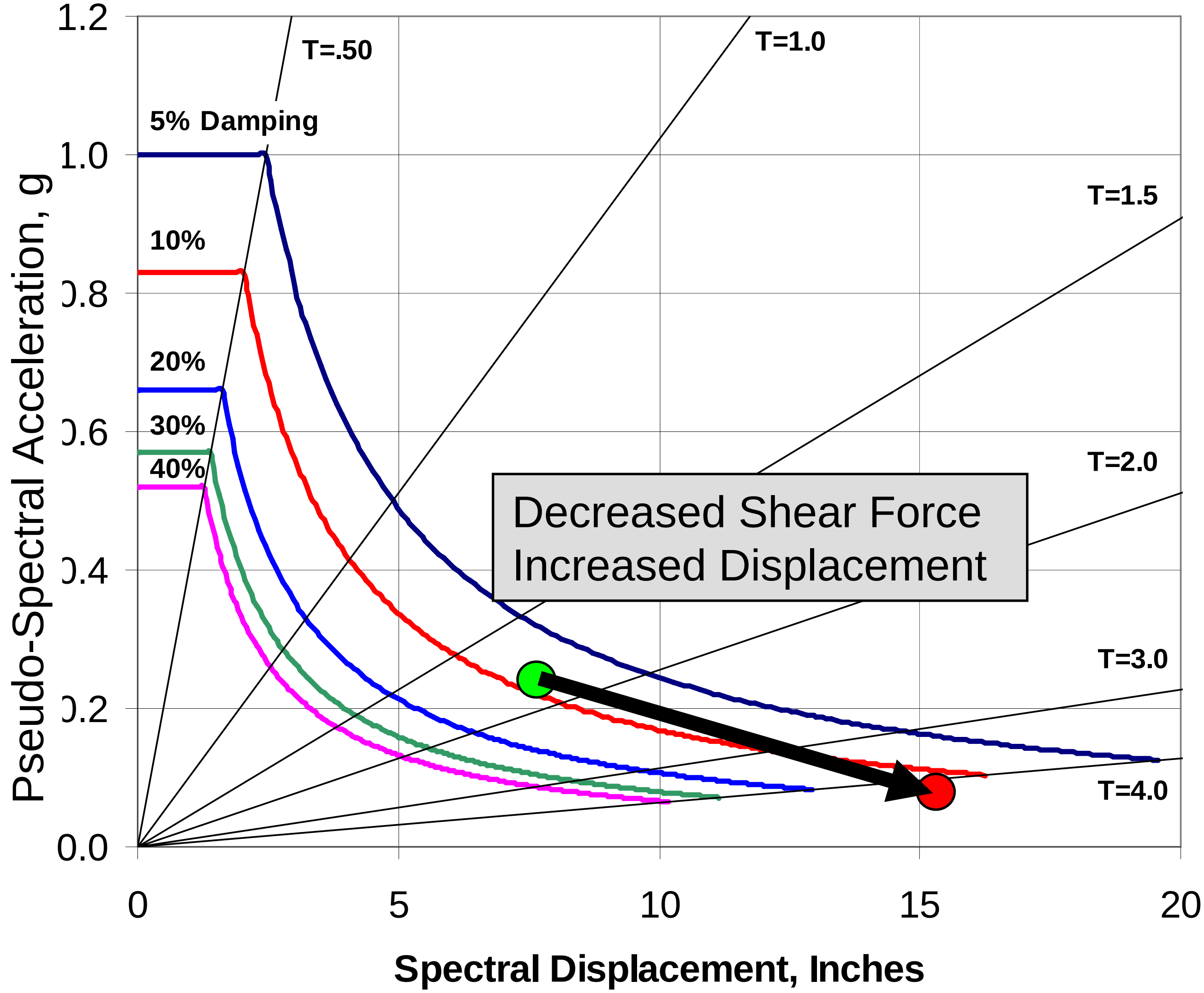
Objectives of Seismic Isolation Systems

- 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

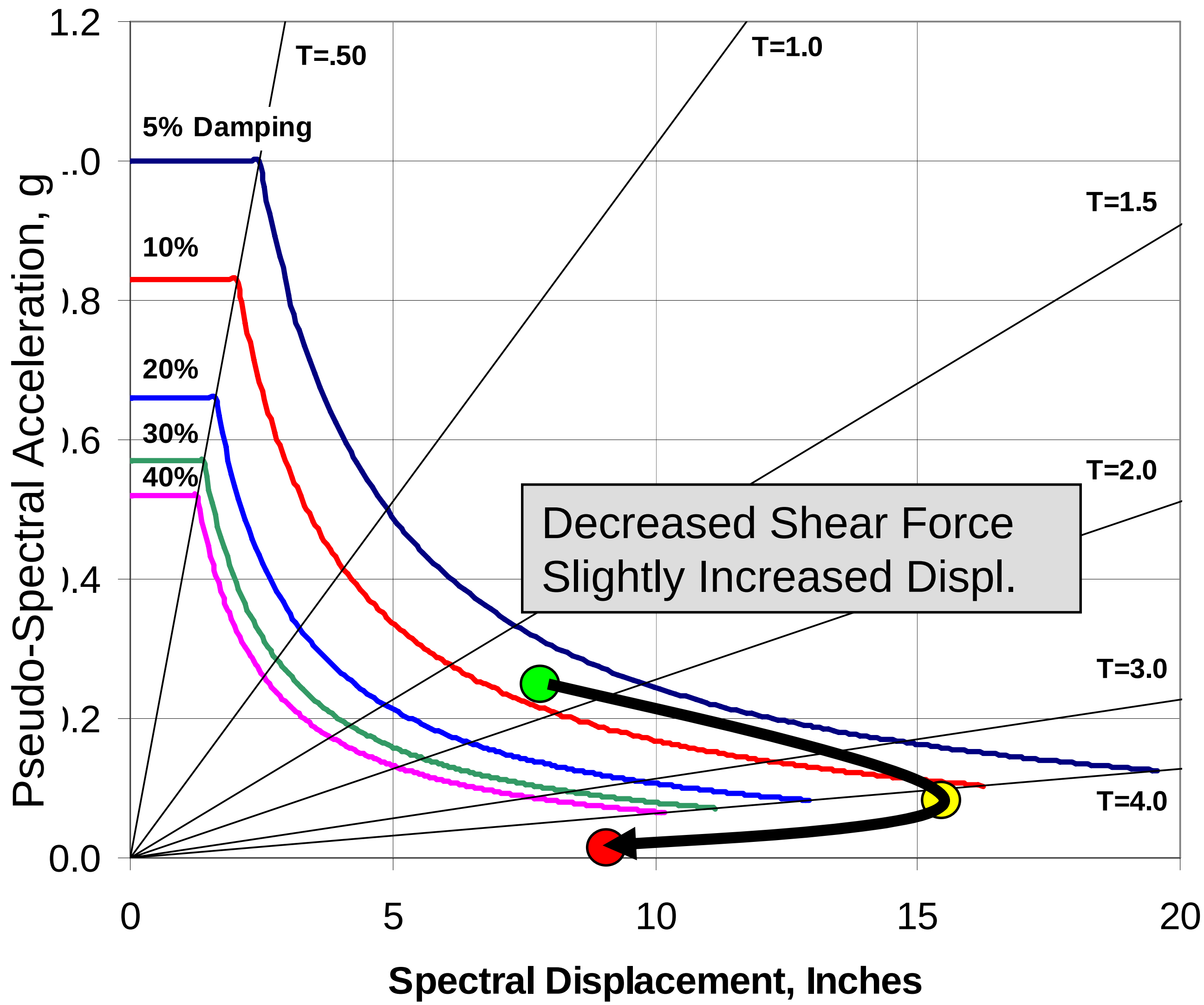
Characteristics of Well-Designed Seismic Isolation Systems

- 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

Effect of Seismic Isolation (ADRS Perspective)

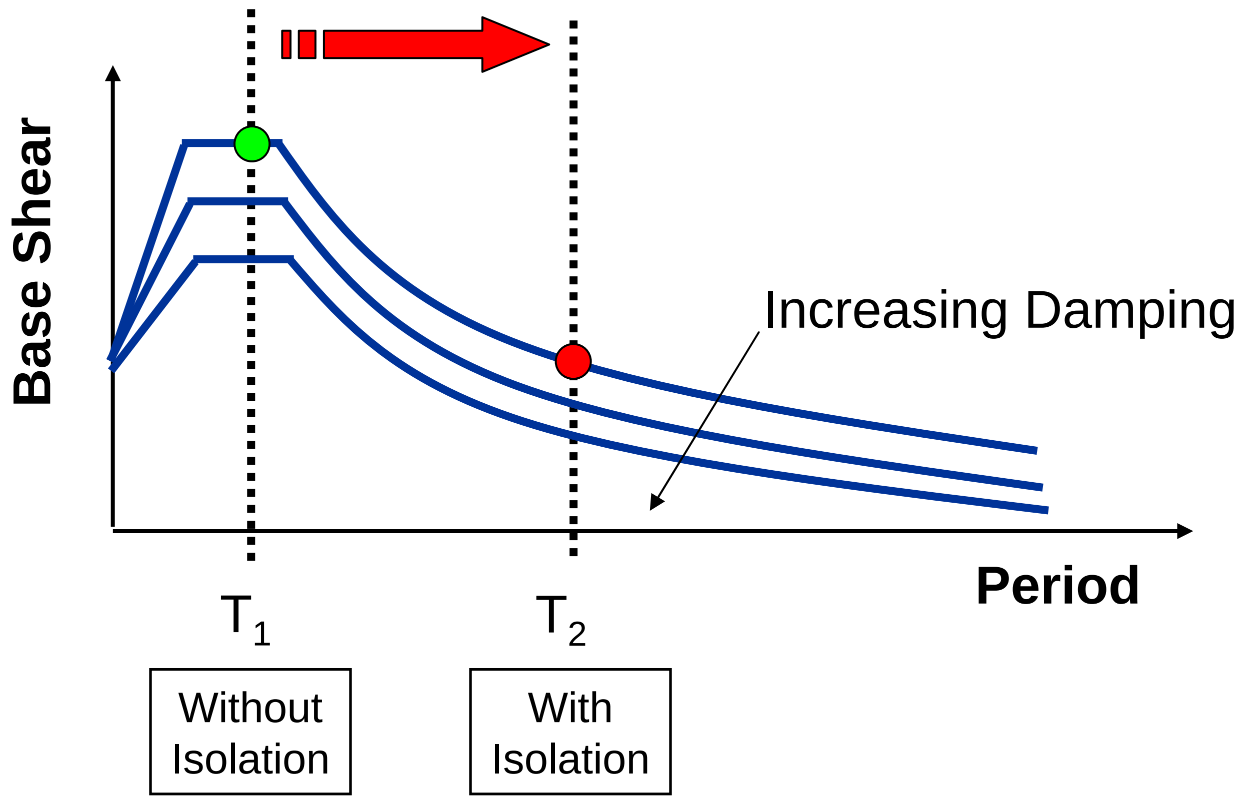


Effect of Seismic Isolation with Supplemental Dampers
(ADRS Perspective)



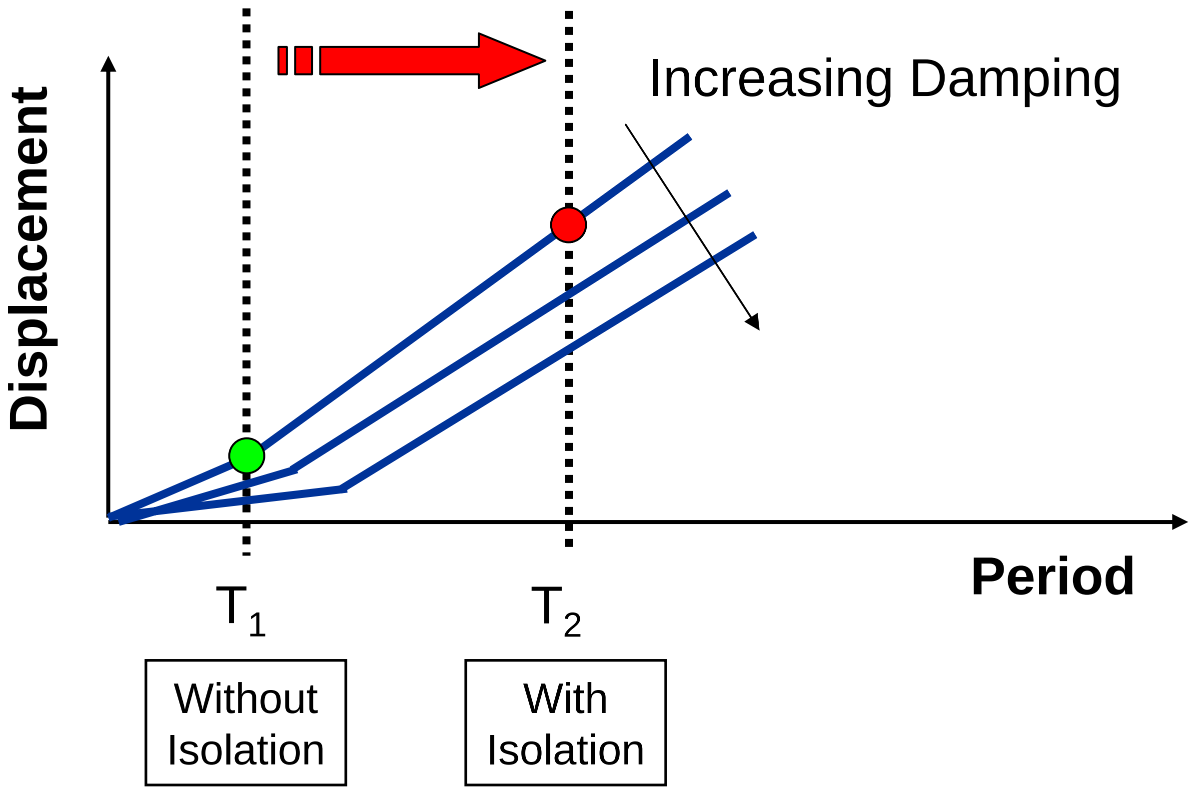
Effect of Seismic Isolation
(Acceleration Response Spectrum Perspective)

Increase Period of Vibration of Structure to Reduce Base Shear

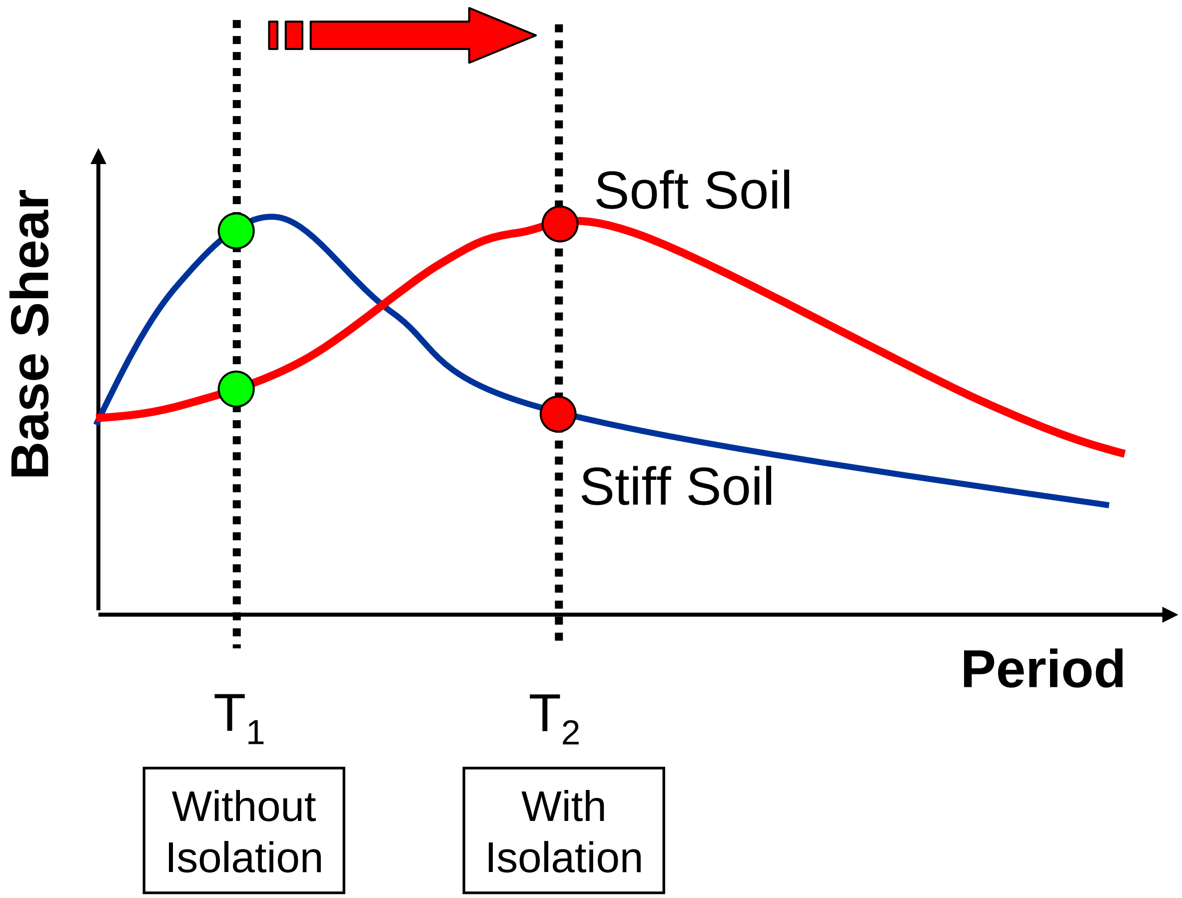


Effect of Seismic Isolation
(Displacement Response Spectrum Perspective)

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



Effect of Soil Conditions on Isolated Structure Response



Applicability of Base Isolation Systems

MOST EFFECTIVE

- Structure on Stiff Soil
- Structure with Low Fundamental Period (Low-Rise Building)

LEAST EFFECTIVE

- Structure on Soft Soil
- Structure with High Fundamental Period (High-Rise Building)

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)

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)

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.

Types of Seismic Isolation Bearings

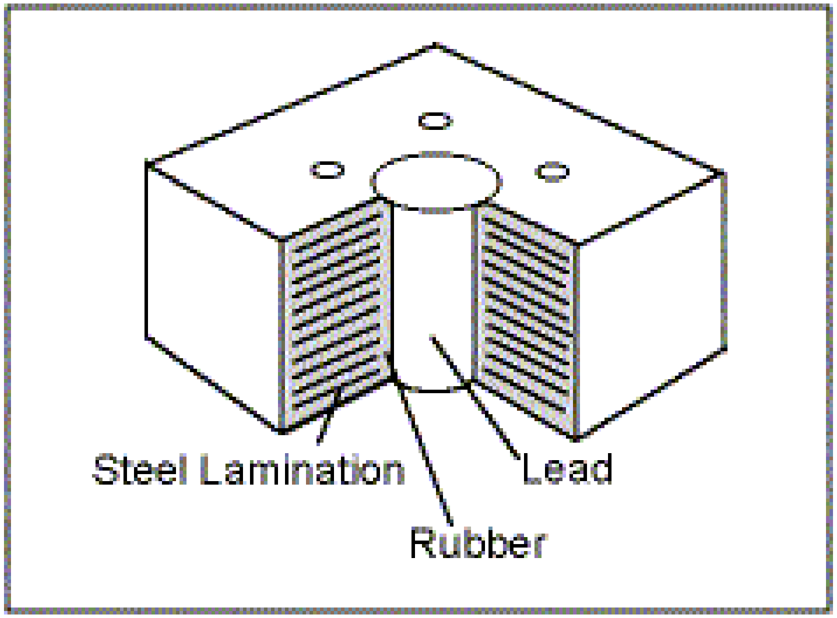
Elastomeric Bearings

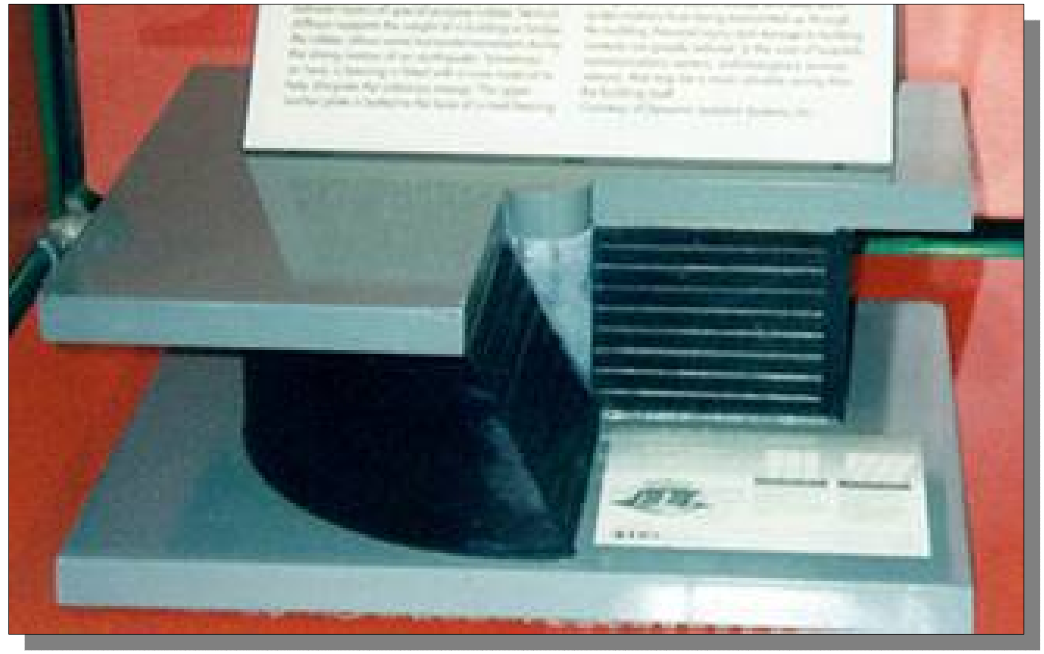
- Low-Damping Natural or Synthetic Rubber Bearing
- High-Damping Natural Rubber Bearing
- Lead-Rubber Bearing
  (Low damping natural rubber with lead core)

Sliding Bearings

- Flat Sliding Bearing
- Spherical Sliding Bearing

Geometry of Elastomeric Bearings

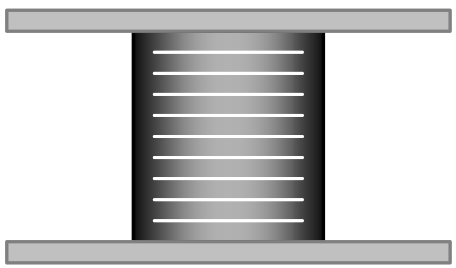




Major Components:

- 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

Low Damping Natural or Synthetic Rubber Bearings



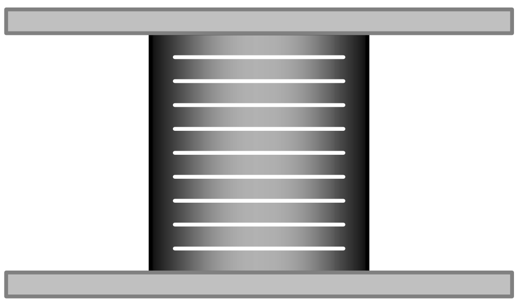
Linear behavior in shear for shear strains up to and exceeding 100%.

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.

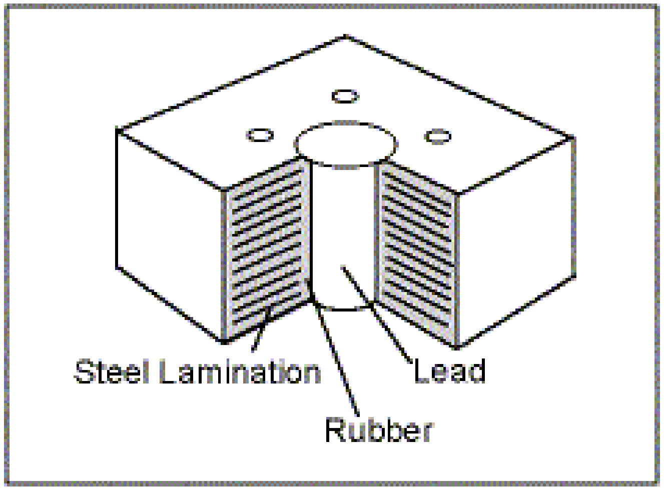
Disadvantage:
Need supplemental damping system

High-Damping Natural Rubber Bearings



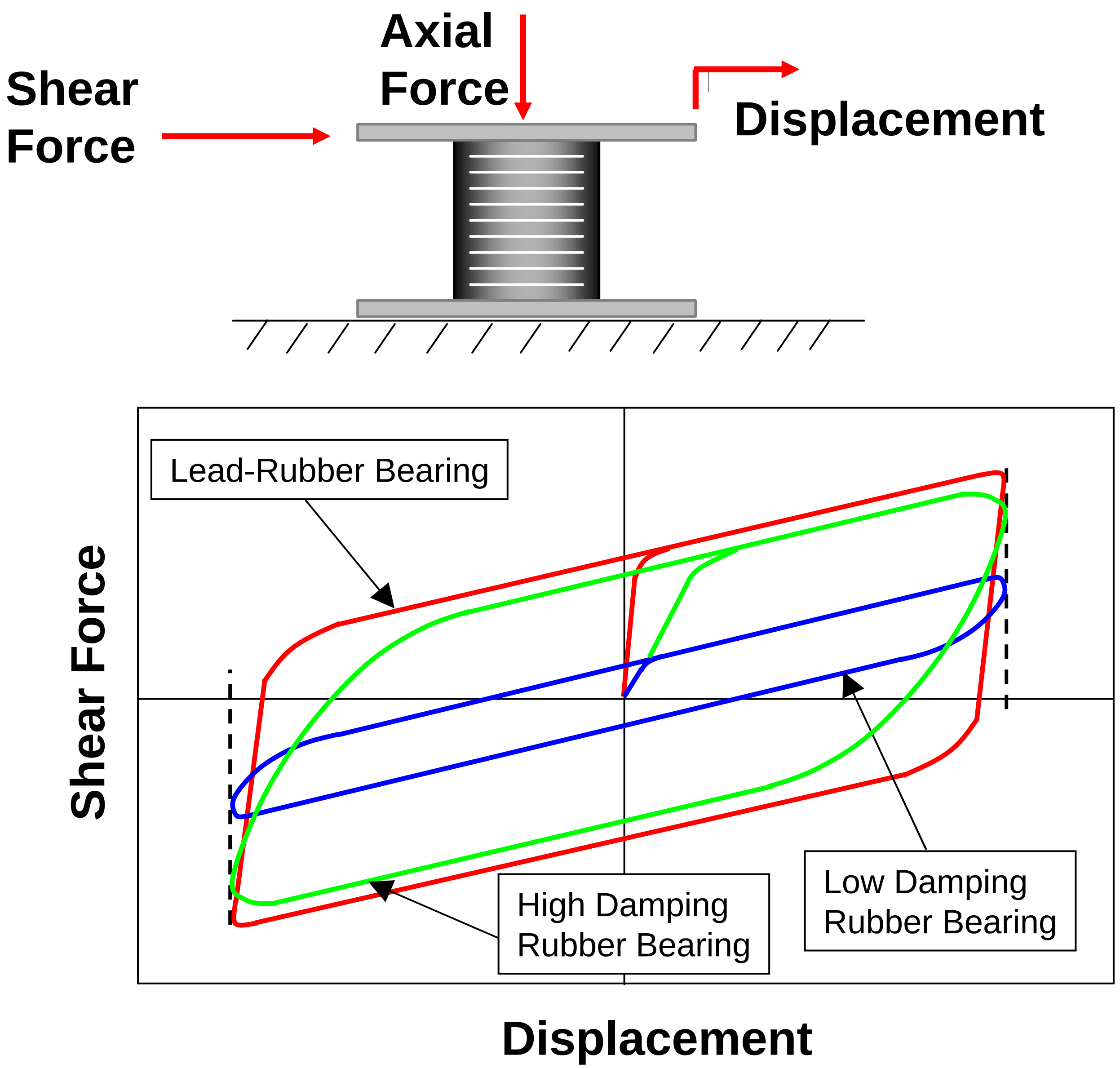
- Maximum shear strain = 200 to 350%
- Damping increased by adding extrafine carbon black, oils or resins, and other proprietary fillers
- Damping ratio = 10 to 20% at shear strains of 100%
- Shear modulus = 50 to 200 psi
- Effective Stiffness and Damping depend on:
  - Elastomer and fillers
  - Contact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

Lead-Rubber Bearings

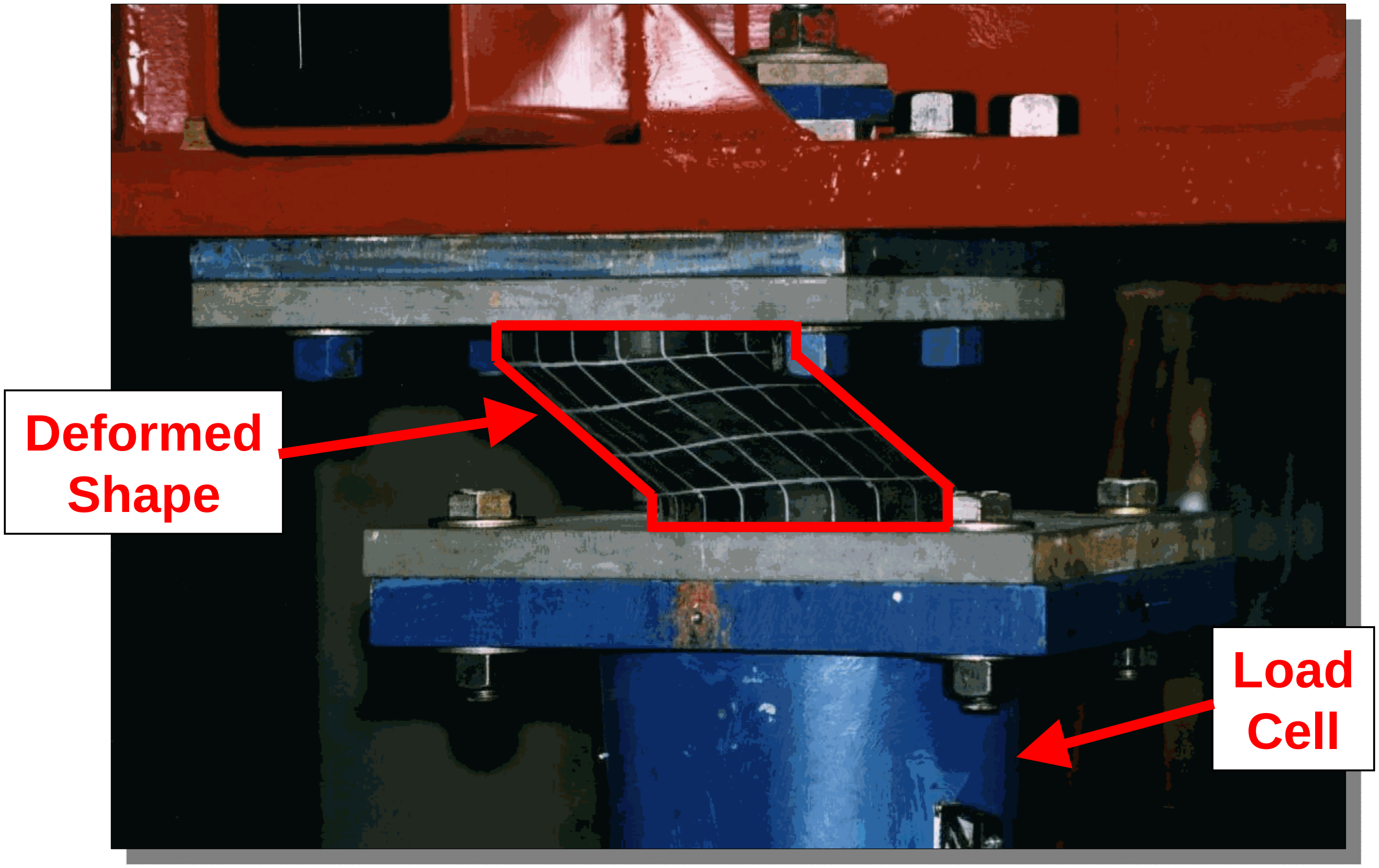


- Solid lead cylinder is press-fitted into central hole of elastomeric bearing
- Lead yield stress = 1500 psi (results in high initial stiffness)
- Invented in 1975 in New Zealand and used extensively in New Zealand, Japan, and the United States.
- Low damping rubber combined with central lead core
- 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

Elastomeric Bearing Hysteresis Loops

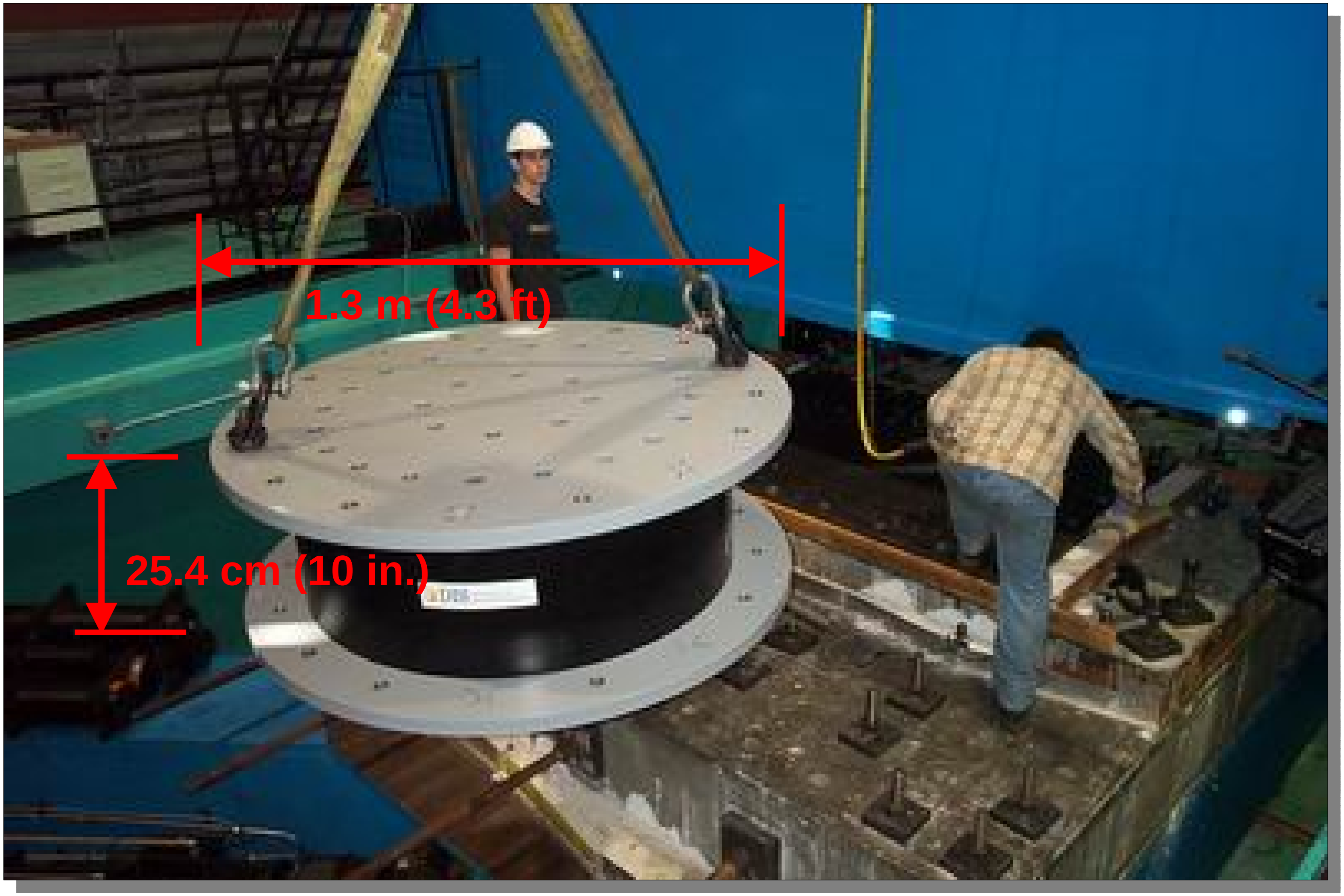


Shear Deformation of Elastomeric Bearing



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

Full-Scale Bearing Prior to Dynamic Testing



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

Harmonic Behavior of Elastomeric Bearing

$$u(t) = u_0 \sin(\overline{\omega} t)$$

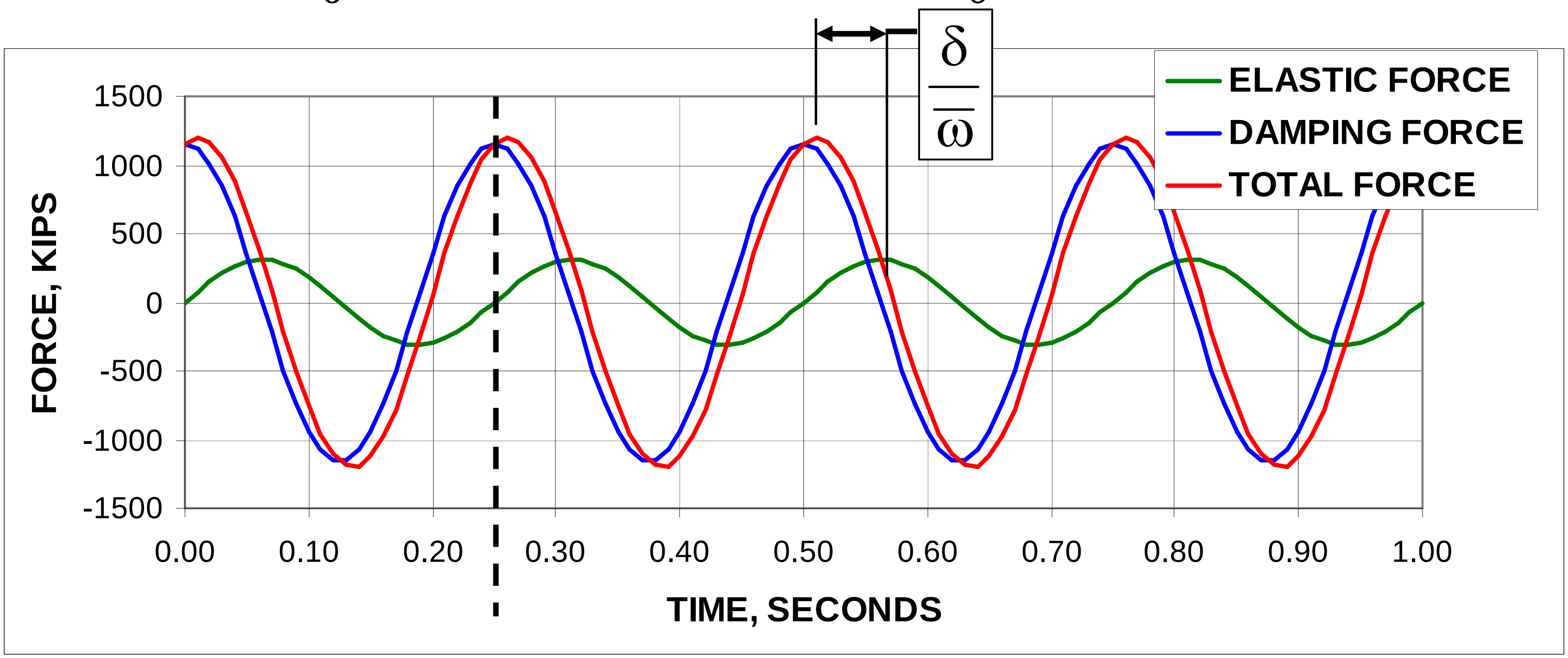
Imposed Motion

Loading Frequency

Phase Angle (Lag)

Assumed Form of Total Force

$$P(t) = P_0 \sin(\overline{\omega} t)\cos(\delta) + P_0 \cos(\overline{\omega} t)\sin(\delta)$$



Note: Damping force 90º out of phase with elastic force.

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

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

Storage Stiffness

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

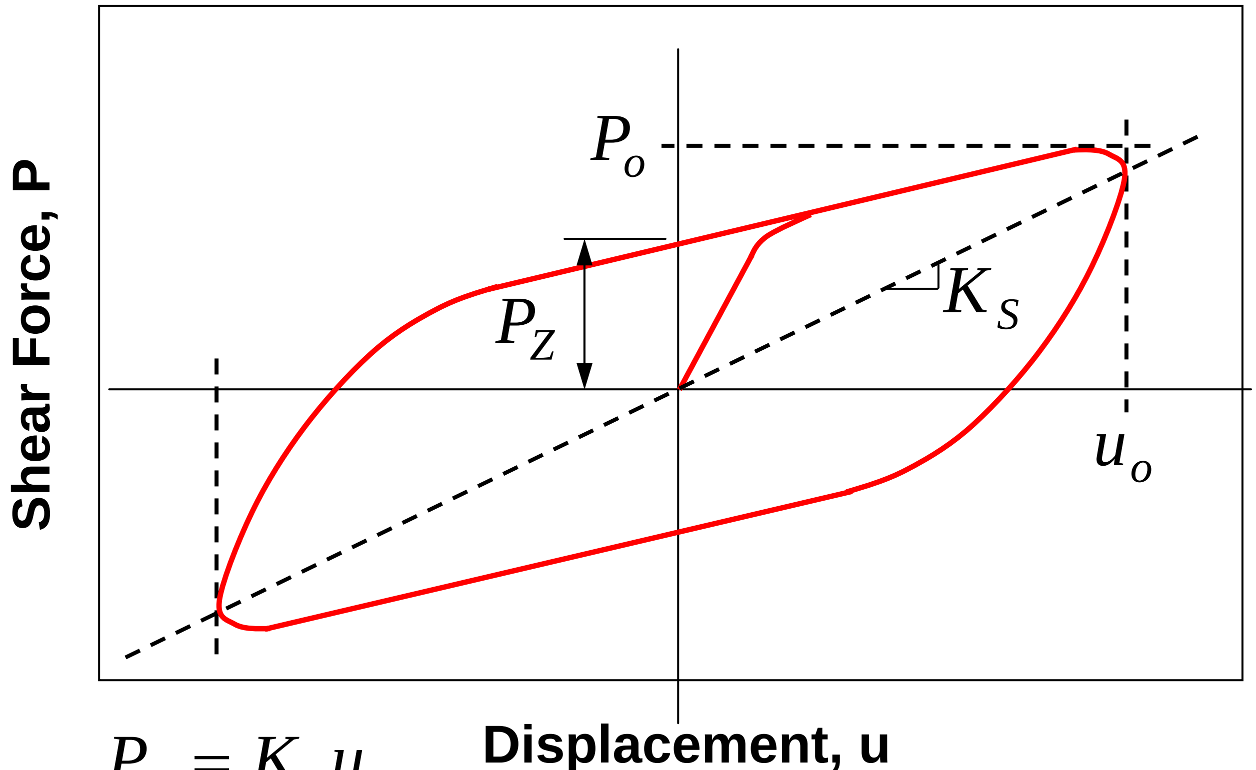
Loss Stiffness

$$C = \frac{K_L}{\overline{\omega}}$$

Damping Coeff.

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

Phase Angle



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

$$P_Z = K_L u_o$$

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

$$K_S = \frac{G' A}{t_r}$$

Storage Stiffness

$$K_L = \frac{G'' A}{t_r}$$

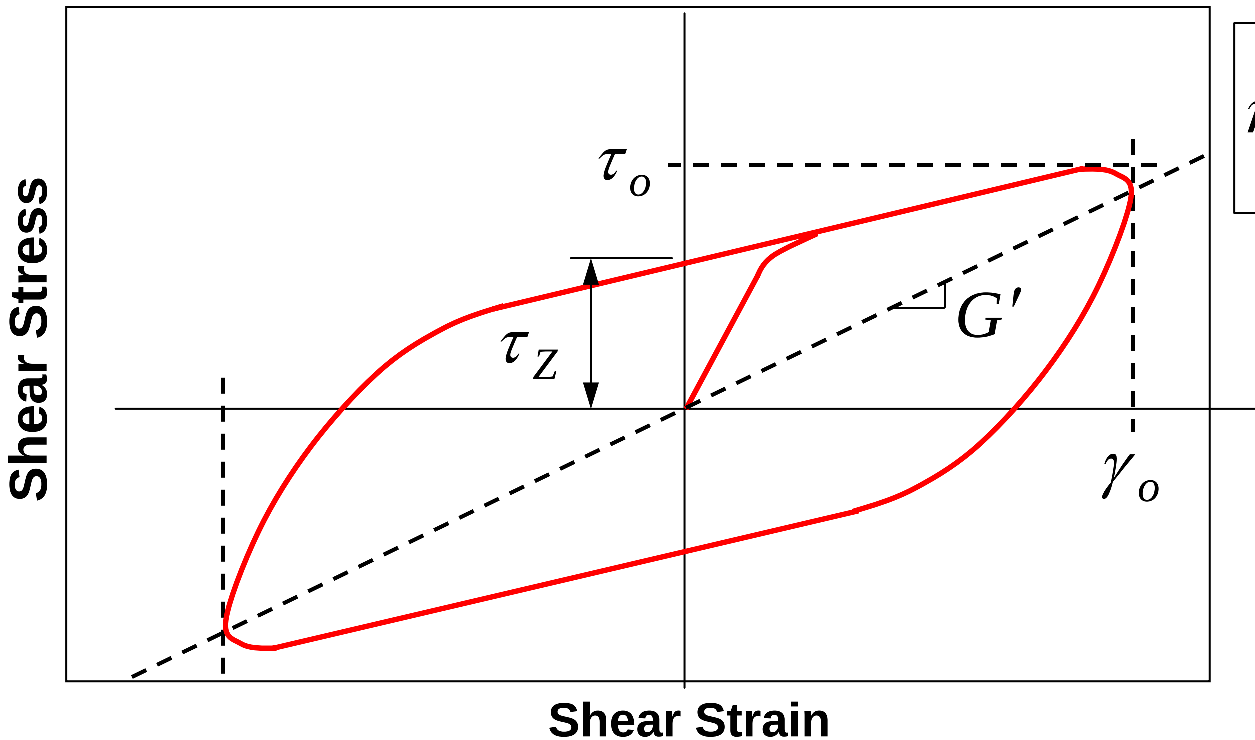
Loss Stiffness

$$C = \frac{K_L}{\overline{\omega}}$$

Damping Coeff.

$$\delta = \sin^{-1}\left(\frac{\tau_Z}{\tau_0}\right)$$

Phase Angle



$$\eta = \frac{G''(\overline{\omega})}{G'(\overline{\omega})} = tan(\delta)$$

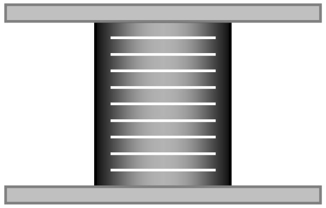
Loss Factor

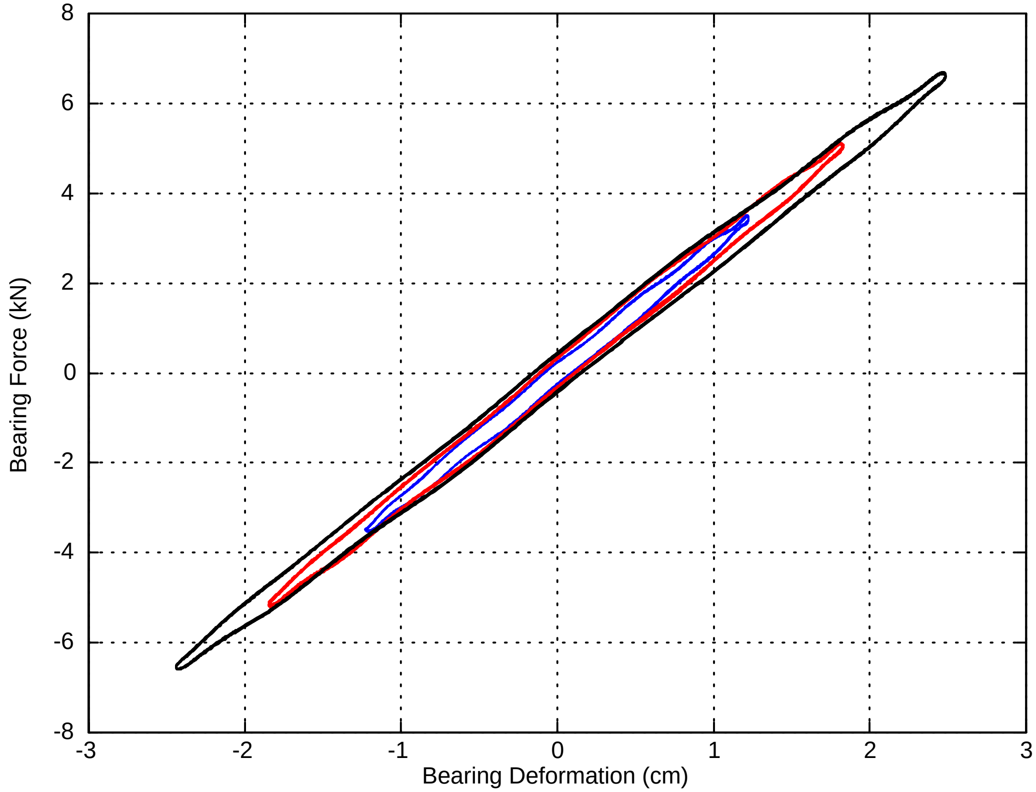
$$\xi = \frac{\eta}{2} = \frac{1}{2} tan(\delta)$$

Damping Ratio

$$\tau(t) = G'\gamma(t) + G''\dot{\gamma}(t) / \overline{\omega}$$

Experimental Hysteresis Loops of Low Damping Rubber Bearing

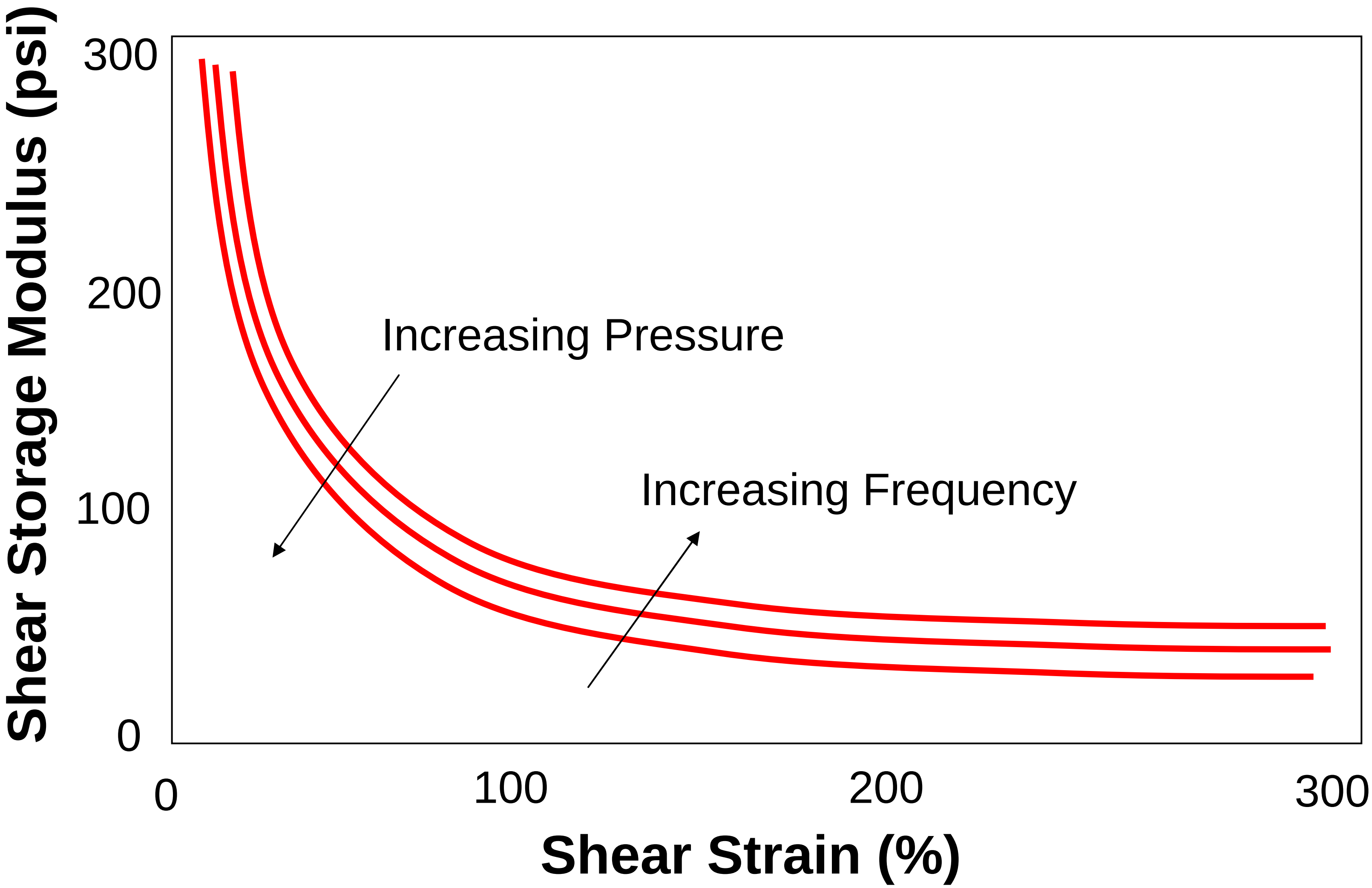




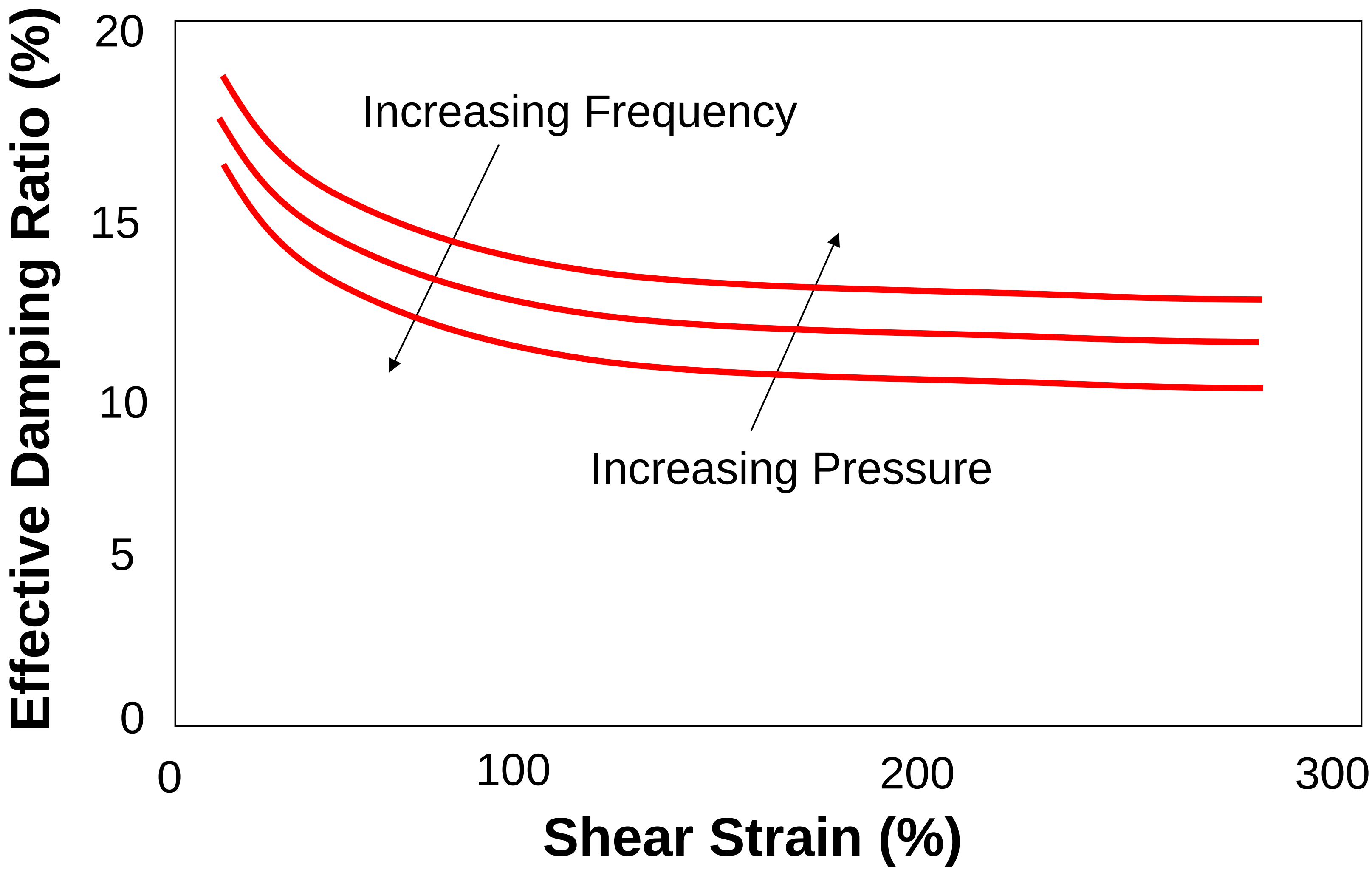
Low Damping Rubber Bearing

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

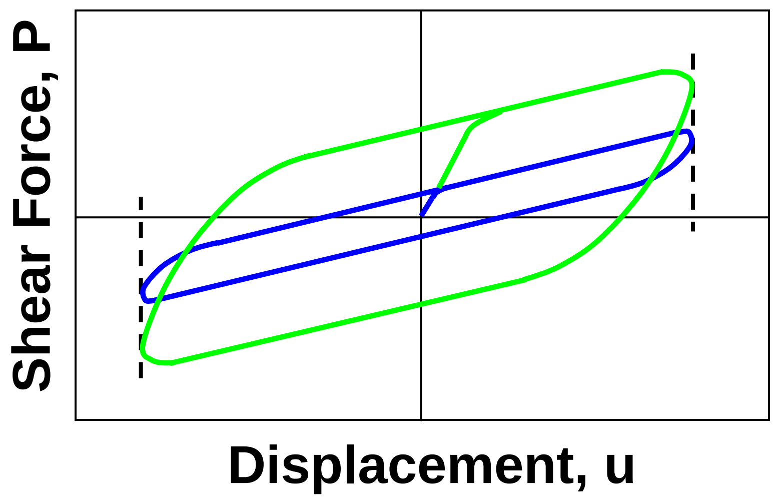
Shear Storage Modulus of High-Damping Natural Rubber



Effective Damping Ratio of High-Damping Natural Rubber

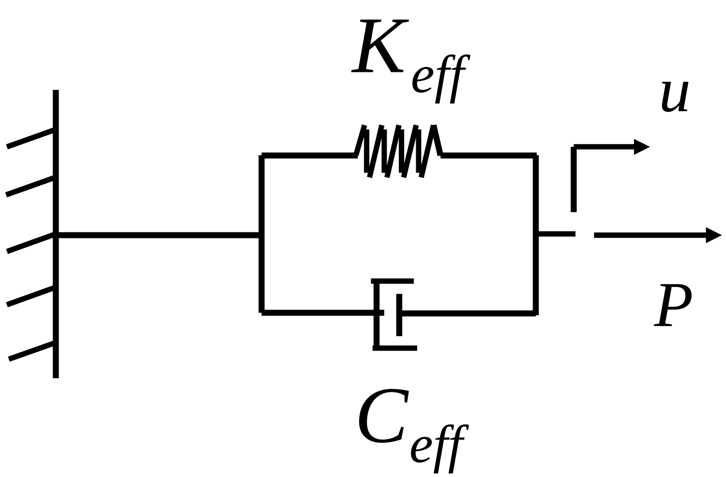


Linear Mathematical Model for Natural and Synthetic Rubber Bearings



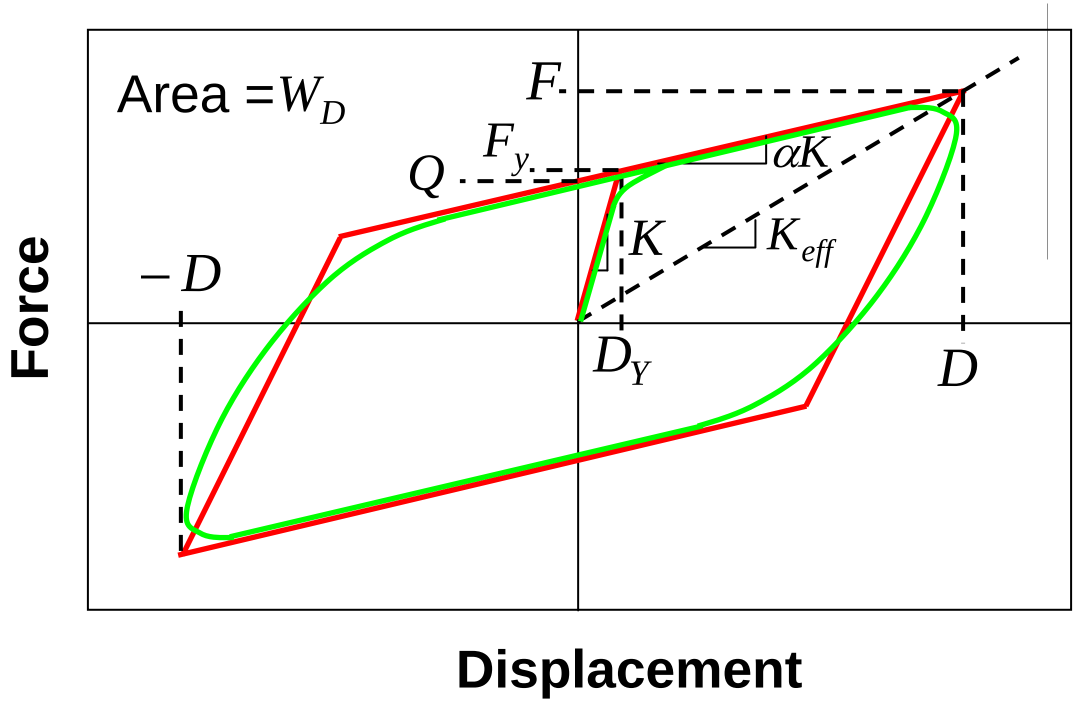
k_{eff} = Effective stiffness at design displacement

c_{eff} = Effective damping coefficient associated with design displacement



$$P(t) = k_{eff}\,u(t) + c_{eff}\,\dot{u}(t)$$

Equivalent Linear Properties from Idealized Bilinear Hysteresis Loop



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

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

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

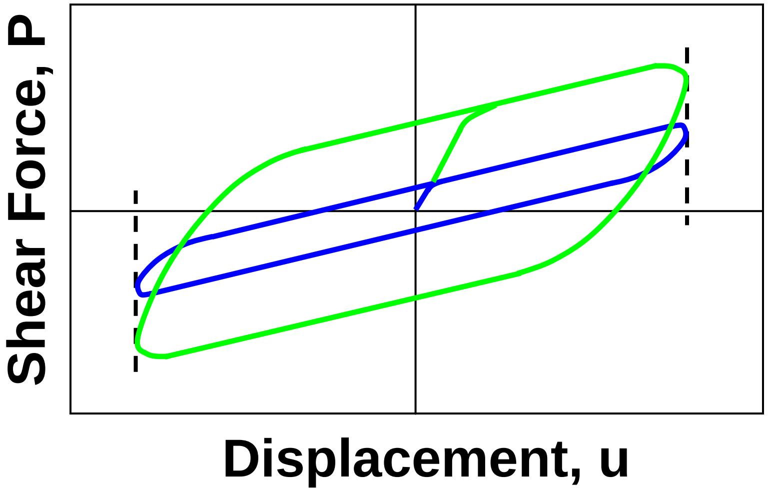
$$W_S = \frac{1}{2} K_{eff} D^2$$

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

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

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

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

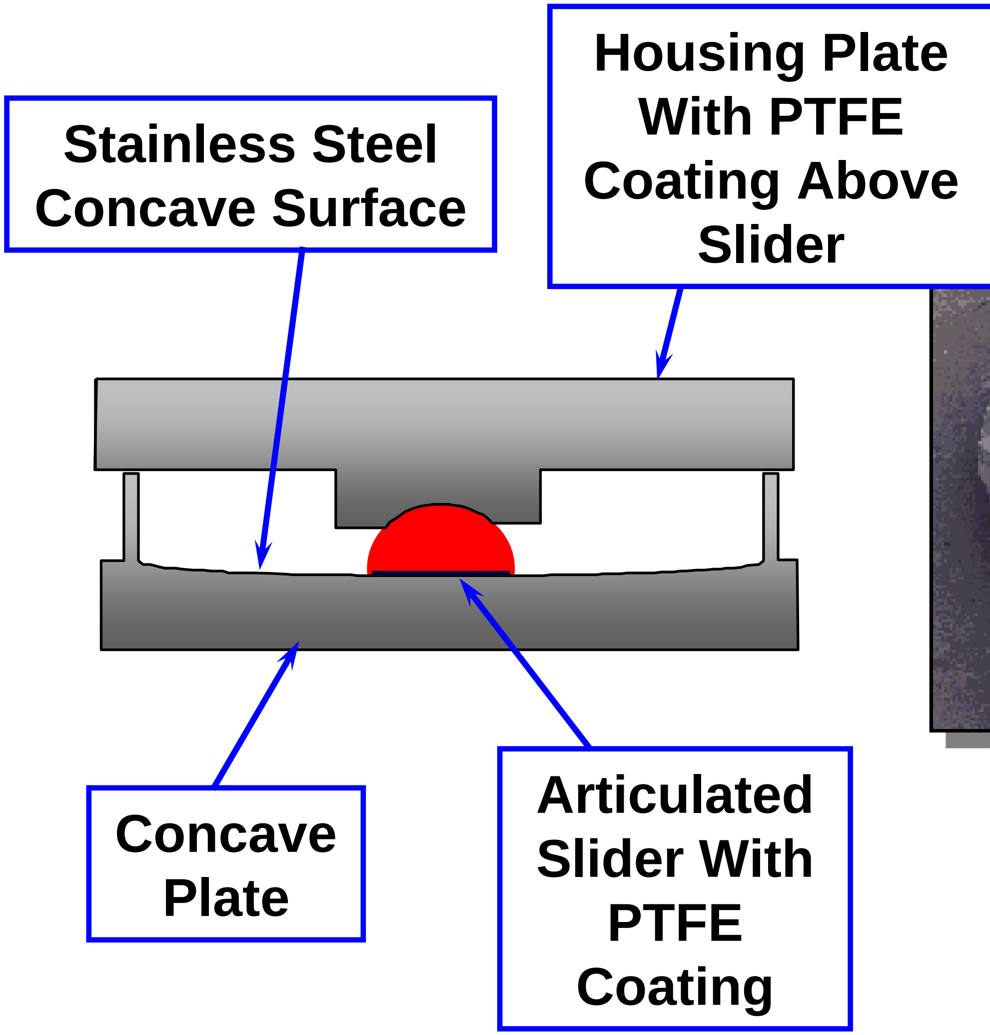
Z = Evolutionary variable

$\gamma, \beta, \eta, \theta$ = 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*

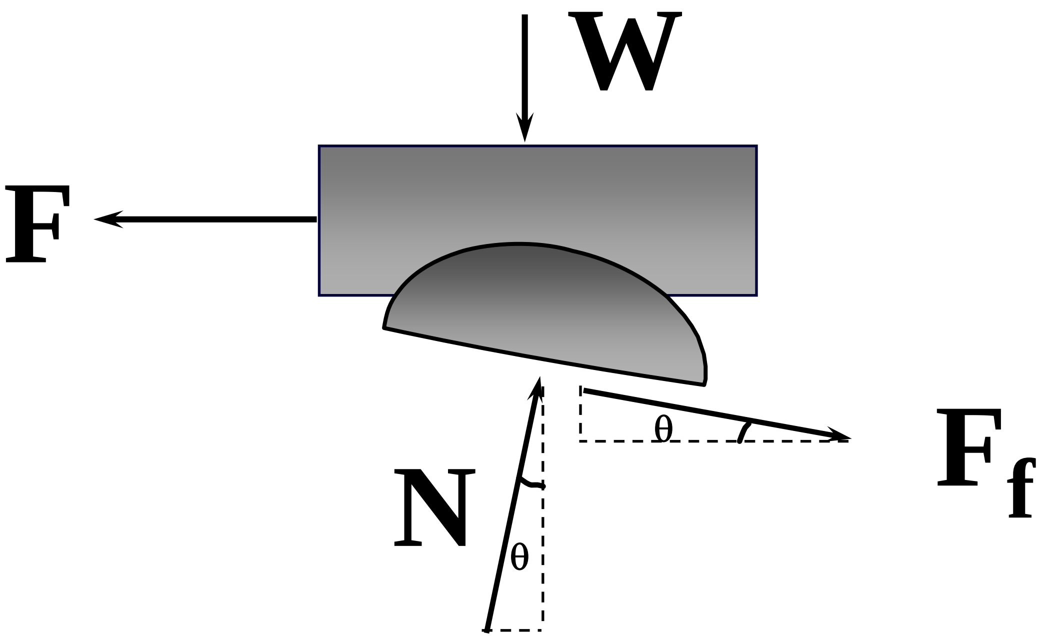
Spherical Sliding Bearing: Friction Pendulum System (FPS)



Concave Plate and Slider for FPS Bridge Bearing

- **Seismic retrofit of Benicia-Martinez Bridge, San Francisco, CA**
- **7.5 to 13 ft diameters**
- **Displ. Capacity of 13 ft bearings = +/- 4.3 ft**

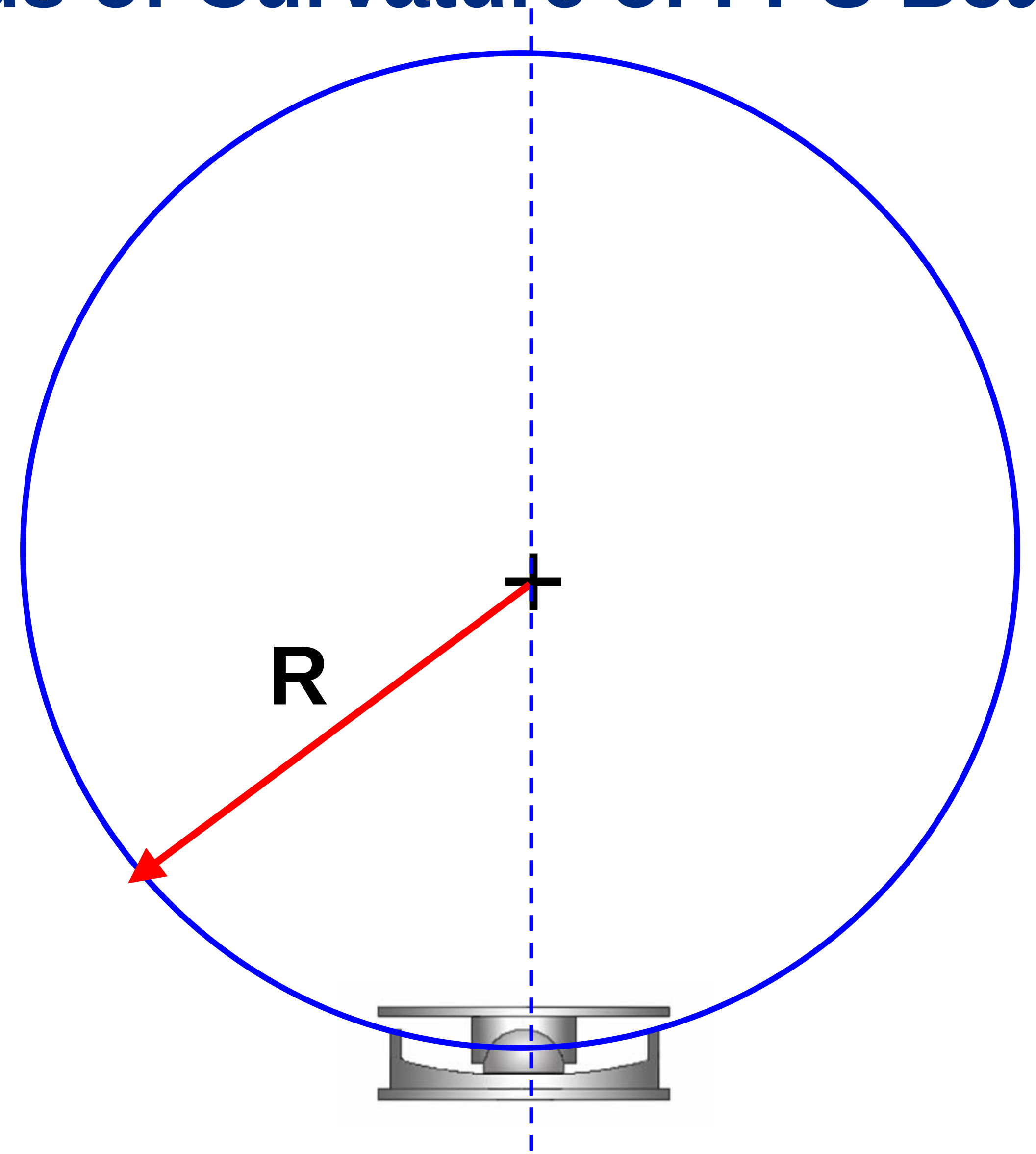
Mathematical Model of Friction Pendulum System Bearings



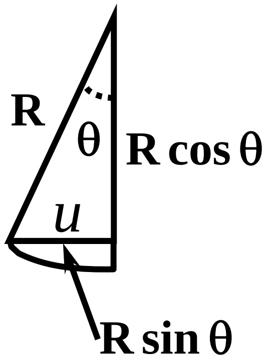
Free-Body Diagram of Top Plate and Slider Under Imposed Lateral Force F

$$F = W \tan\theta + \frac{F_f}{\cos\theta}$$

Radius of Curvature of FPS Bearings



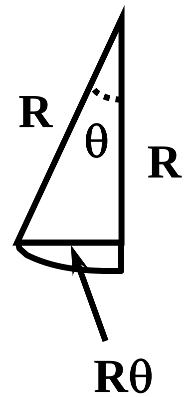
Mathematical Model of Friction Pendulum System Bearings



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

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

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

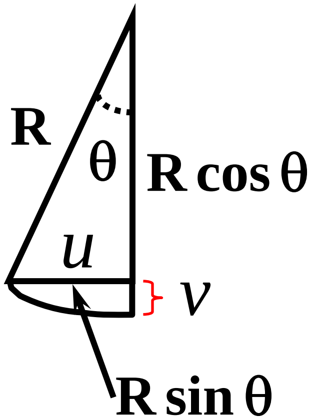


$$\theta \approx \frac{u}{R} \qquad N = \frac{W}{\cos\theta} \approx W$$

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

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

Vertical Displacement of FPS Bearings

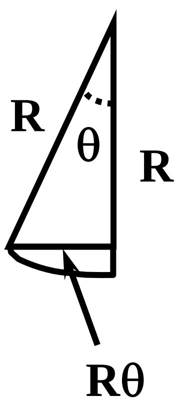


$$v = R(1 - \cos\theta) = R\left[1 - \cos\left(\sin^{-1}\left(\frac{u}{R}\right)\right)\right]$$

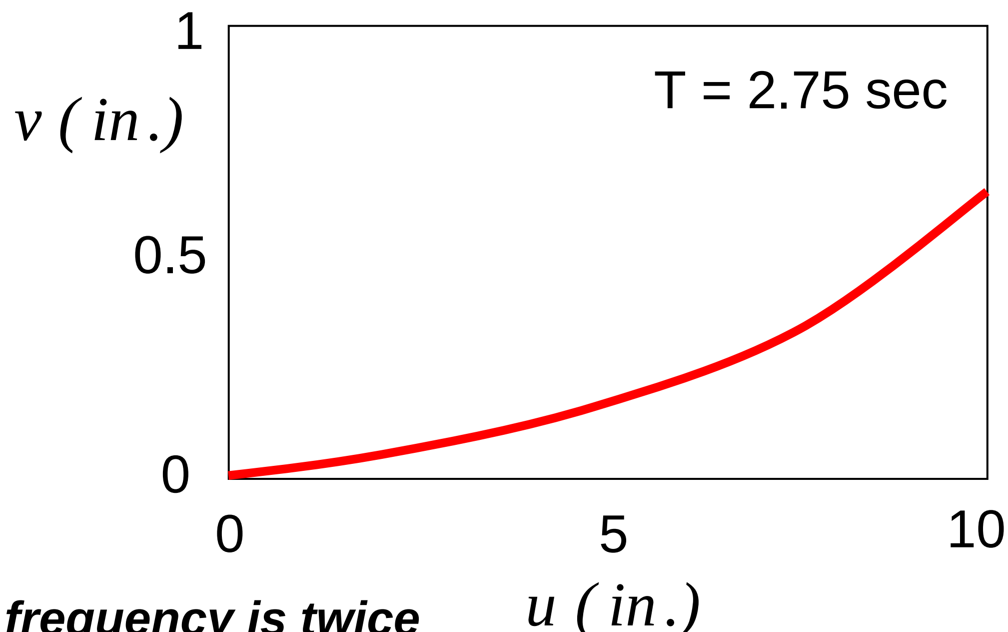
$$v \approx \frac{R\theta^2}{2} \approx \frac{u^2}{2R}$$

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

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



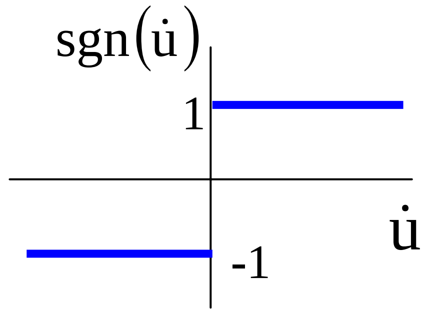
$$\theta \approx \frac{u}{R}$$

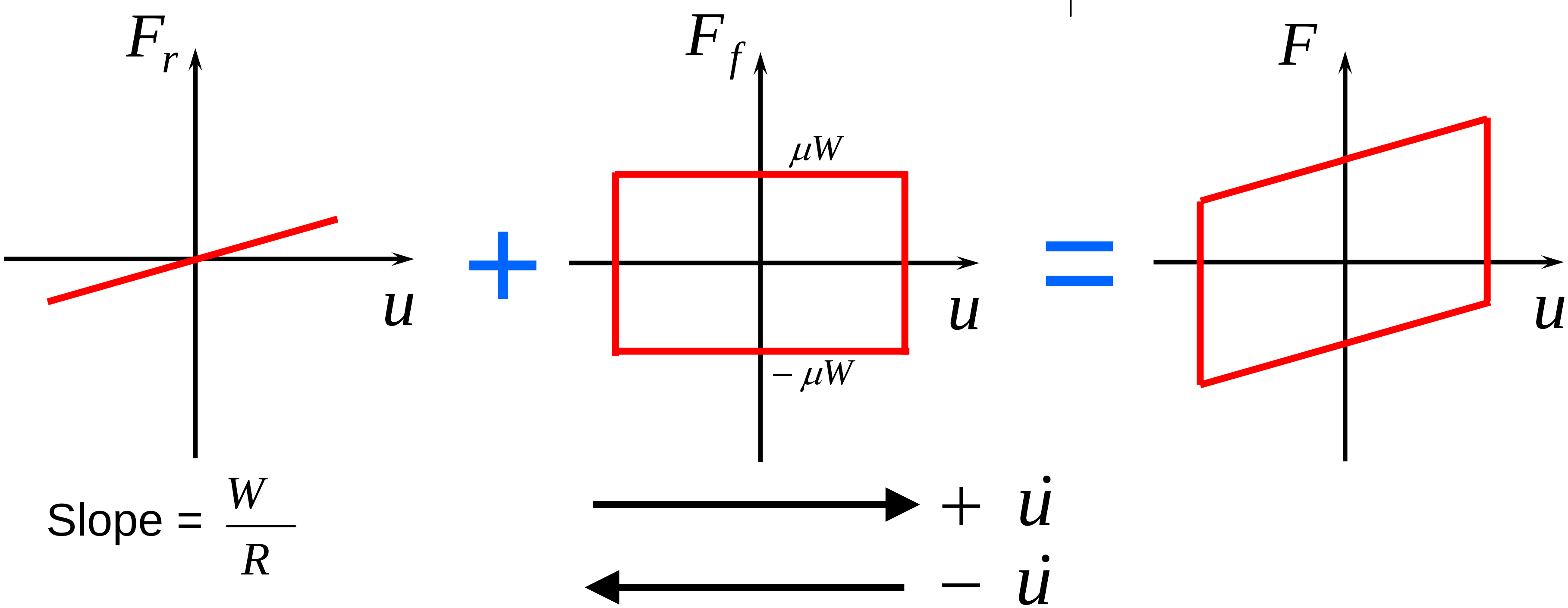


Note: Vertical frequency is twice that of lateral frequency

Components of FPS Bearing Lateral Force

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





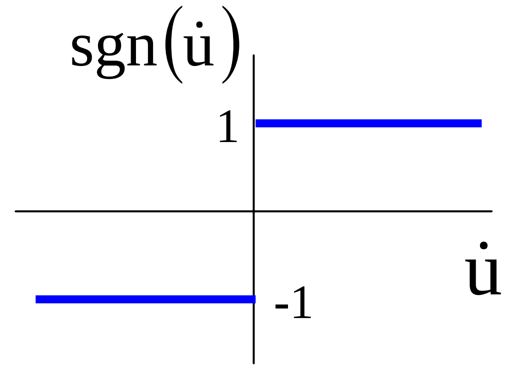
Slope = $\frac{W}{R}$

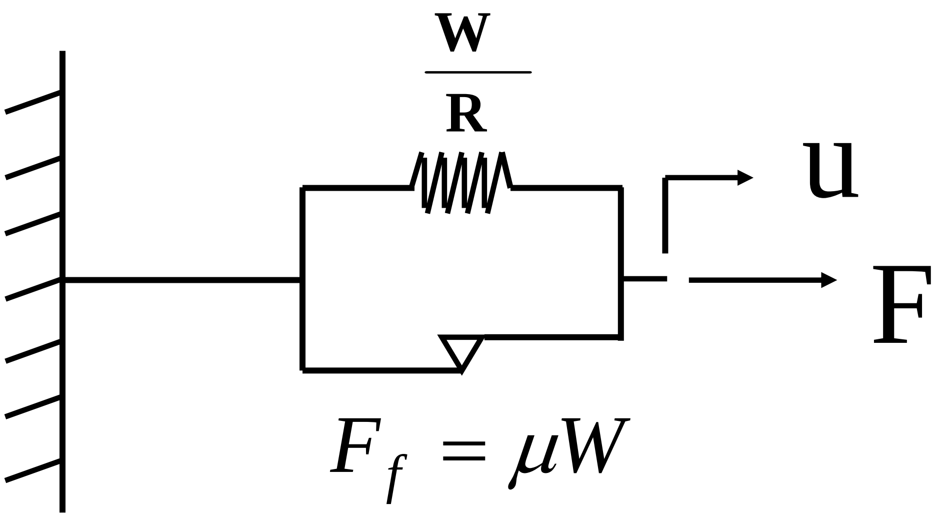
Note: Bearing will not recenter if $F_r < F_f \; (u < \mu R)$

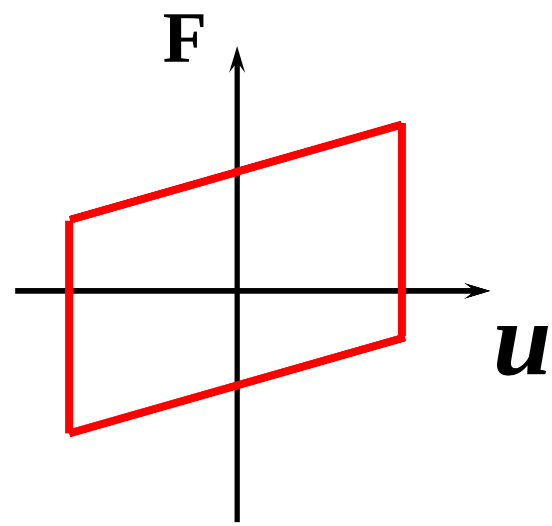
For large T, and thus large R, this can be a concern.

Mechanical Model of Friction Pendulum System Bearings

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







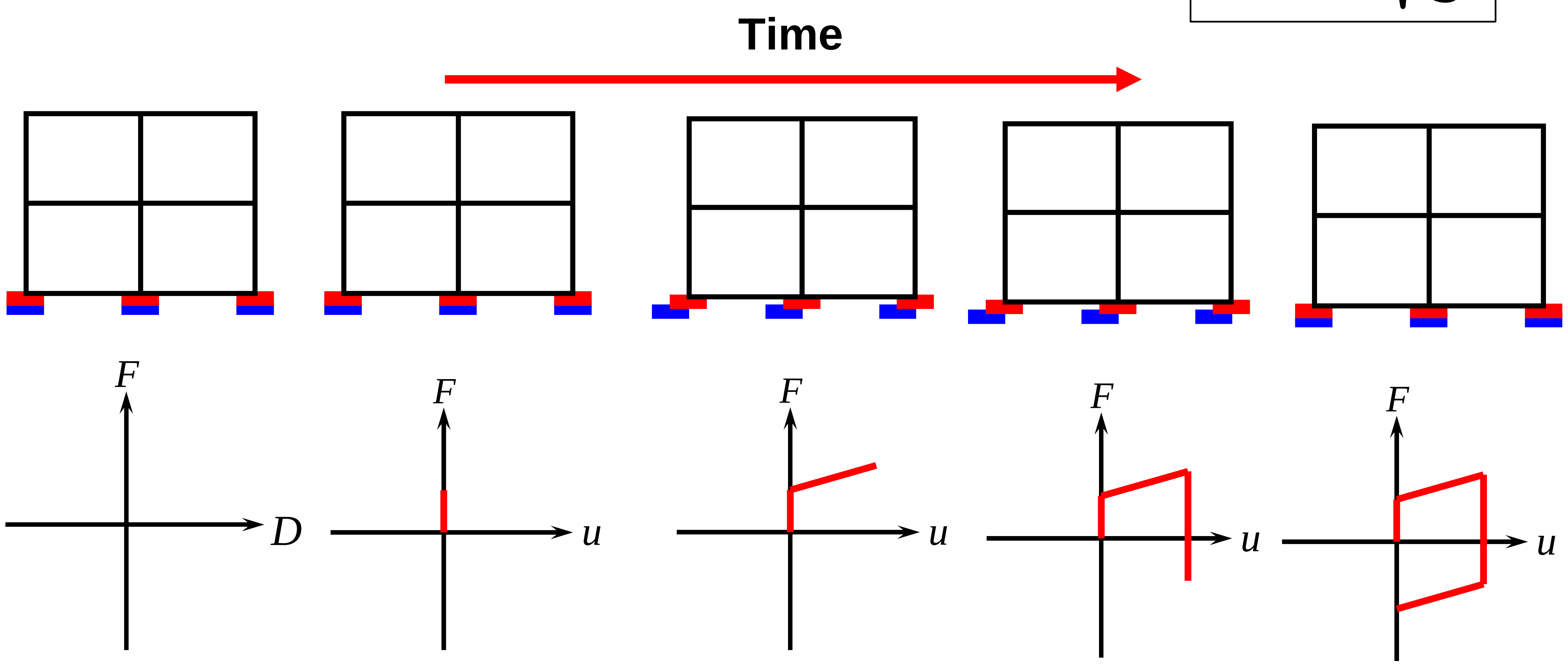
Rigid Model with Strain Hardening

Hysteretic Behavior of Friction Pendulum System Bearings

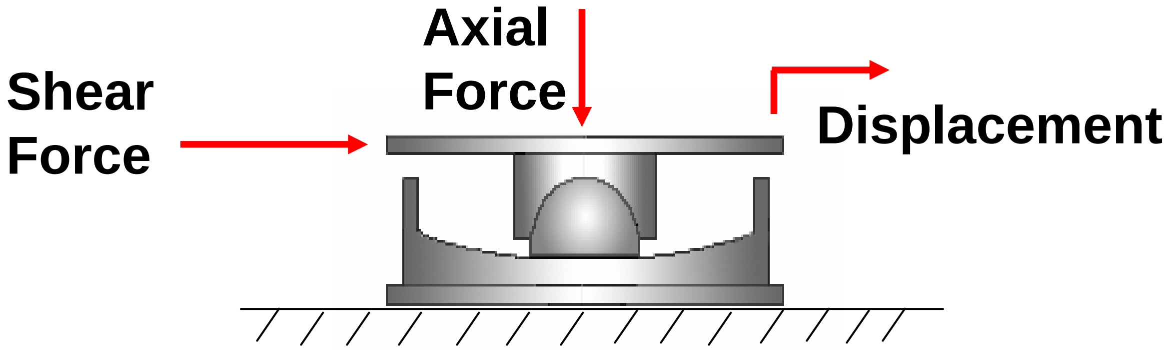
$$F = \frac{W}{R}u + \mu W \, sgn(\dot{u})$$

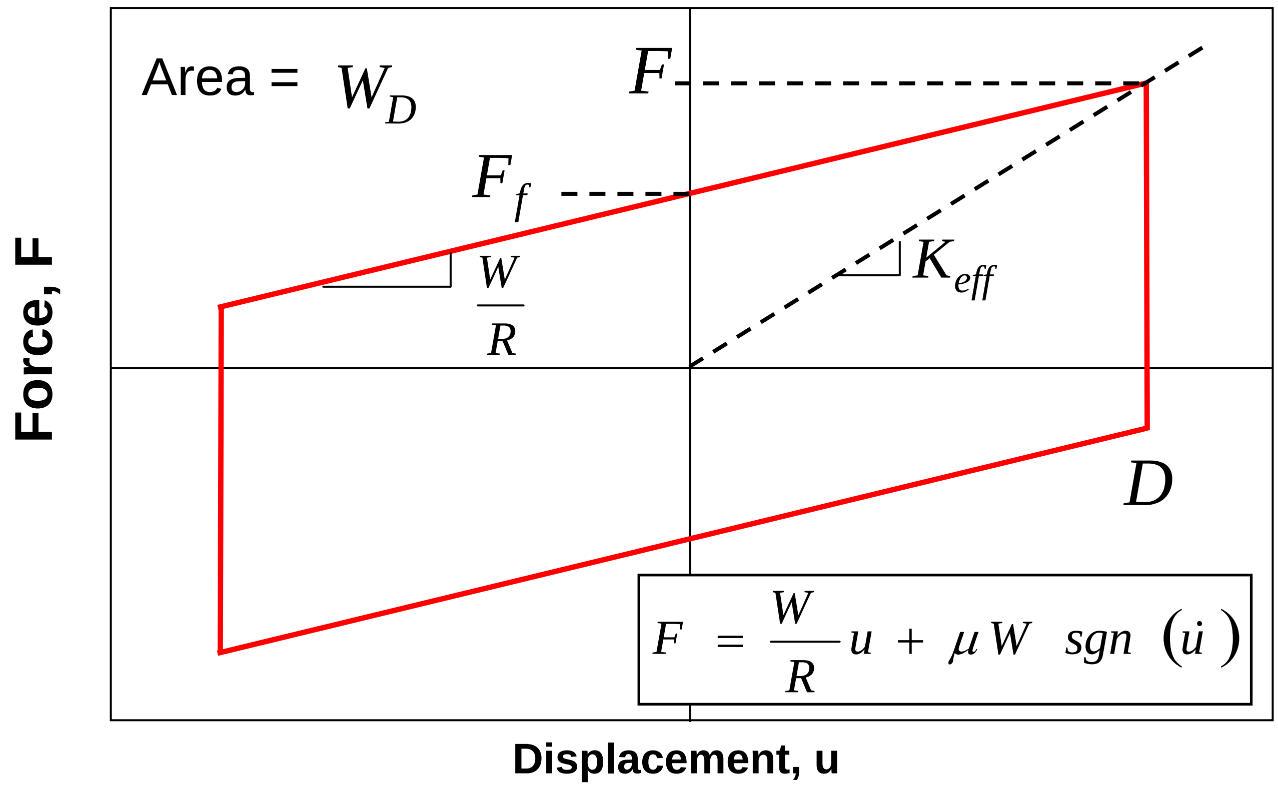
Free Vibration Period

$$T = 2\pi\sqrt{\frac{R}{g}}$$

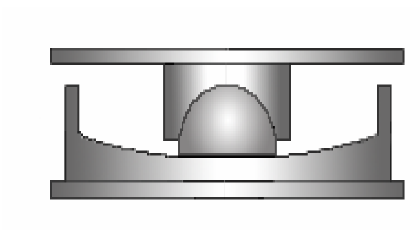


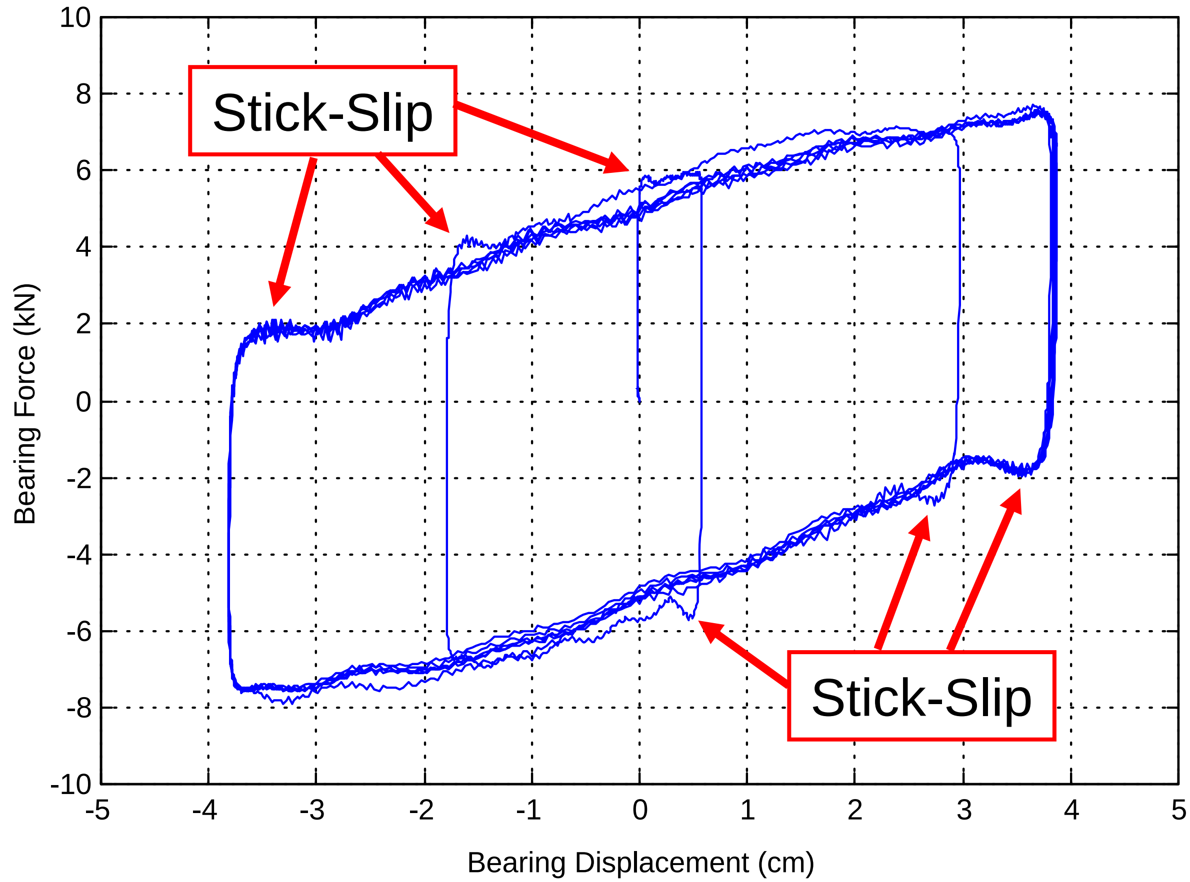
Idealized FPS Bearing Hysteresis Loop





Actual FPS Bearing Hysteresis Loop

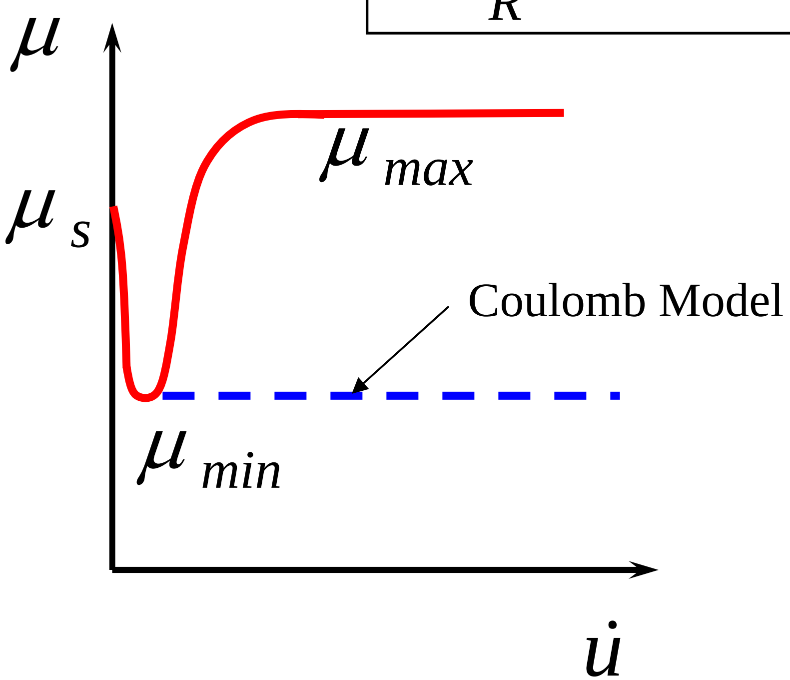




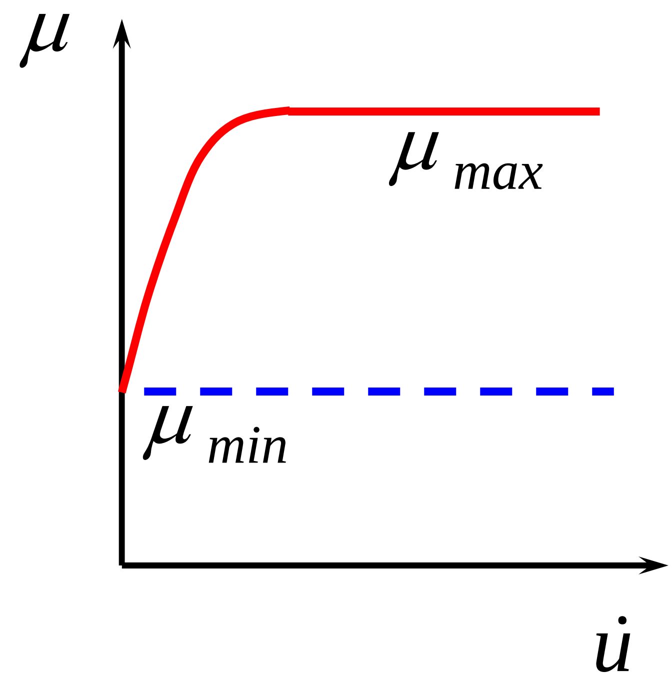
FPS Bearing
- Reduced-scale bearing for ¼-scale building frame
- R = 18.6 in; D = 11 in.; H = 2.5 in. (reduced scale)
- Prototype fundamental period of building = 2.75 sec (R = 74.4 in. = 6.2 ft)

Velocity-Dependence of Coefficient of Friction

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



Actual Velocity-Dependence

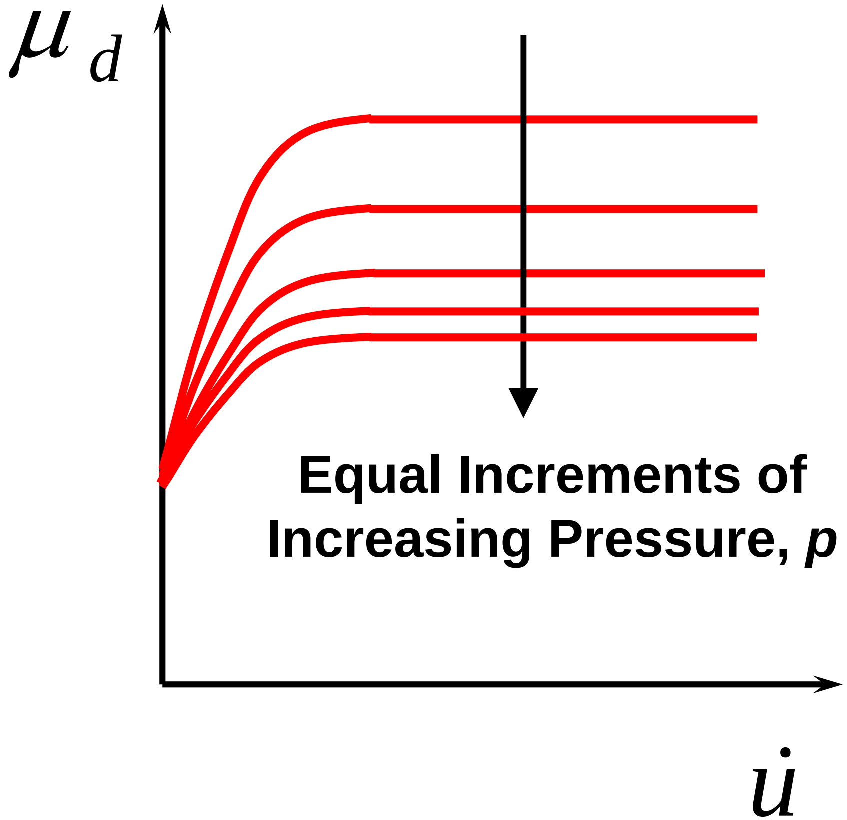


Approximate Velocity-Dependence

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

- Shear strength of PTFE depends on rate of loading.

Pressure-Dependence of Coefficient of Friction



$$p = \frac{W}{A}\left(1 + \frac{\ddot{u}_v}{g} + \frac{P_s}{W}\right)$$

Typically Neglected

Pressure- and Velocity-Dependence

Pressure-Dependence of Coefficient of Friction

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

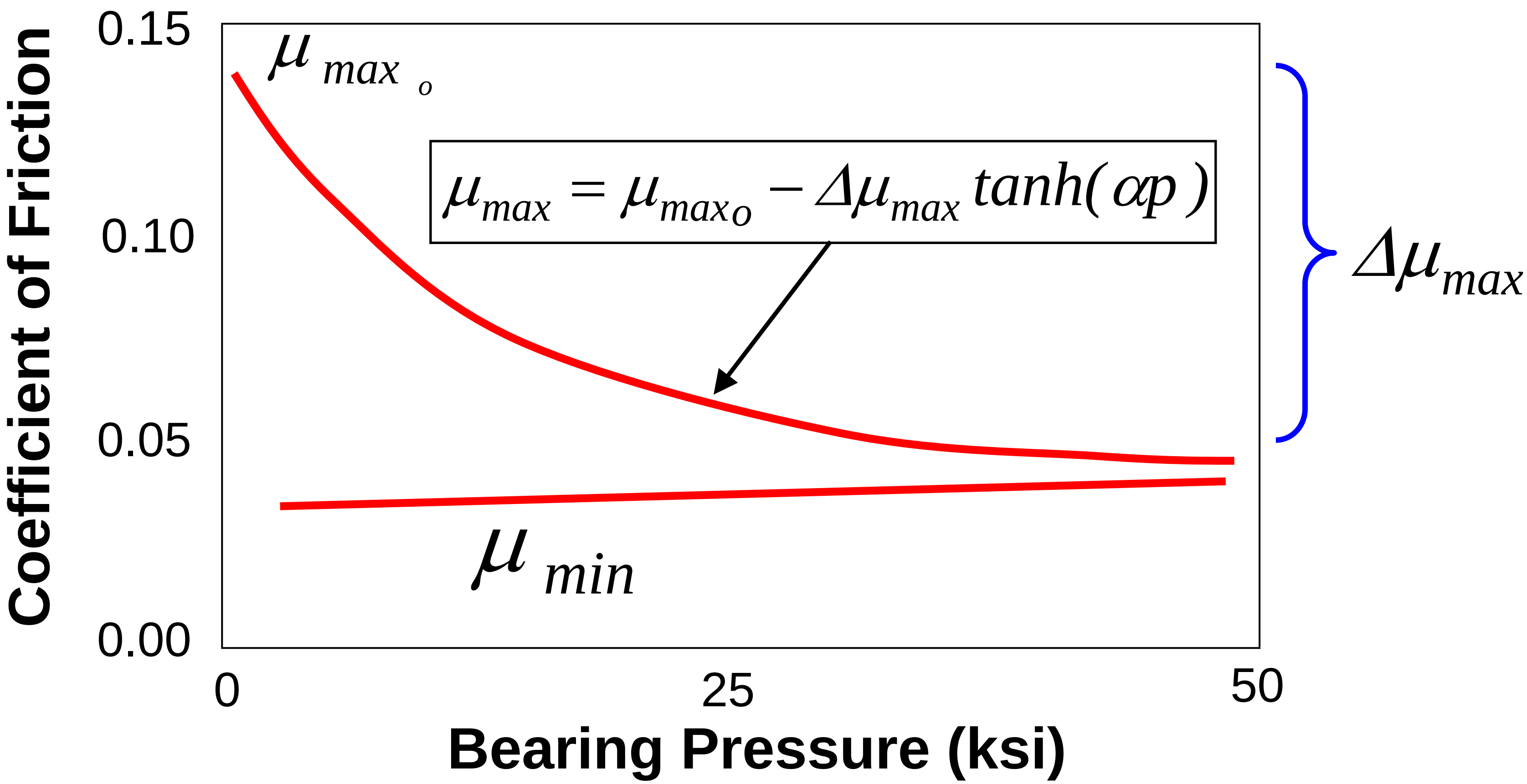
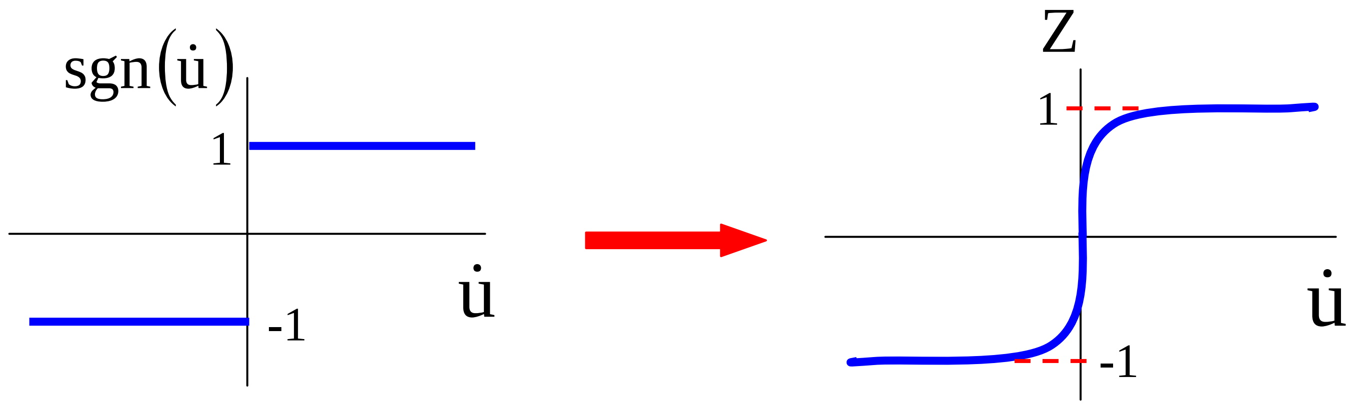


Figure is based on studies of PTFE-based self-lubricating composites used in FPS bearings.

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

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

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

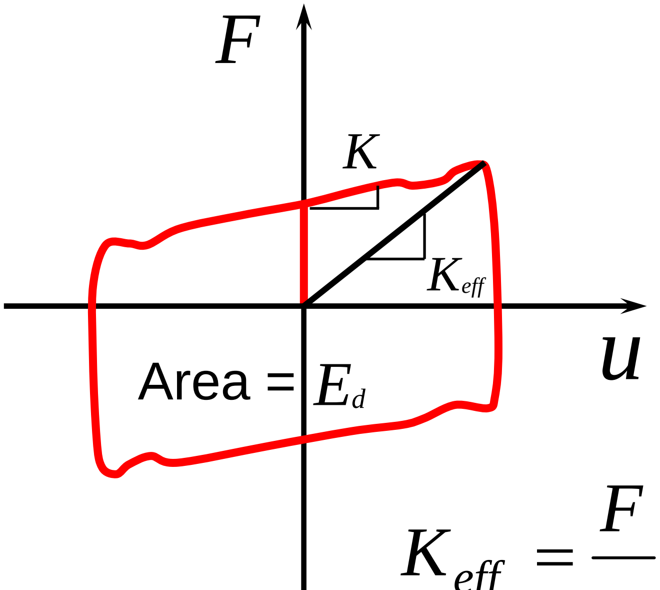
Evaluation of Dynamic Behavior of Base-Isolated Structures

- **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**

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

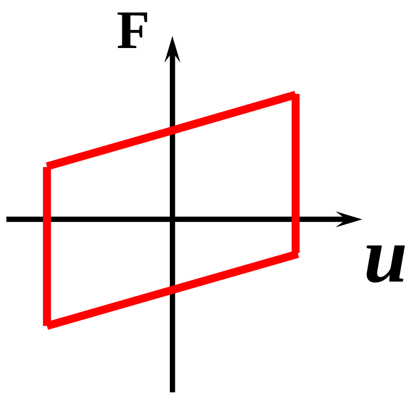
$$\xi_{eff} = \frac{E_d}{4\pi E_s} = \frac{4\mu W u}{4\pi\left(0.5 K_{eff} u^2\right)} = \frac{2\mu R}{\pi\left(\mu R + u\right)}$$

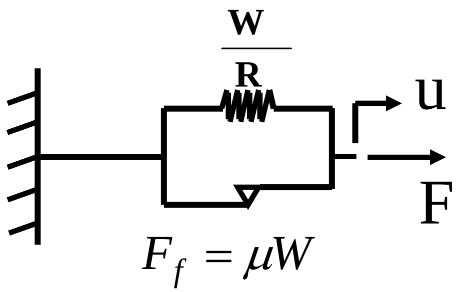
Effective Damping Ratio at Displacement u

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

Seismic Analysis using Nonlinear and Equivalent Linear Models

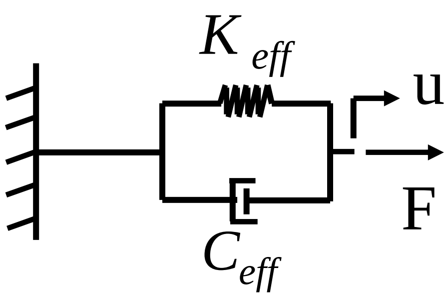
Nonlinear Model



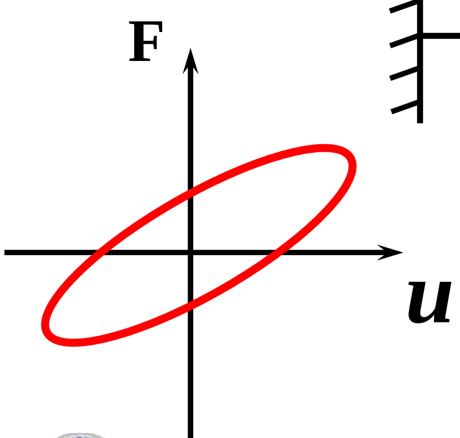


$$F(t) = \frac{W}{R} u(t) + \mu W \, sgn(\dot{u})$$

Linear Model



$$F(t) = K_{eff} u(t) + C_{eff} \dot{u}(t)$$

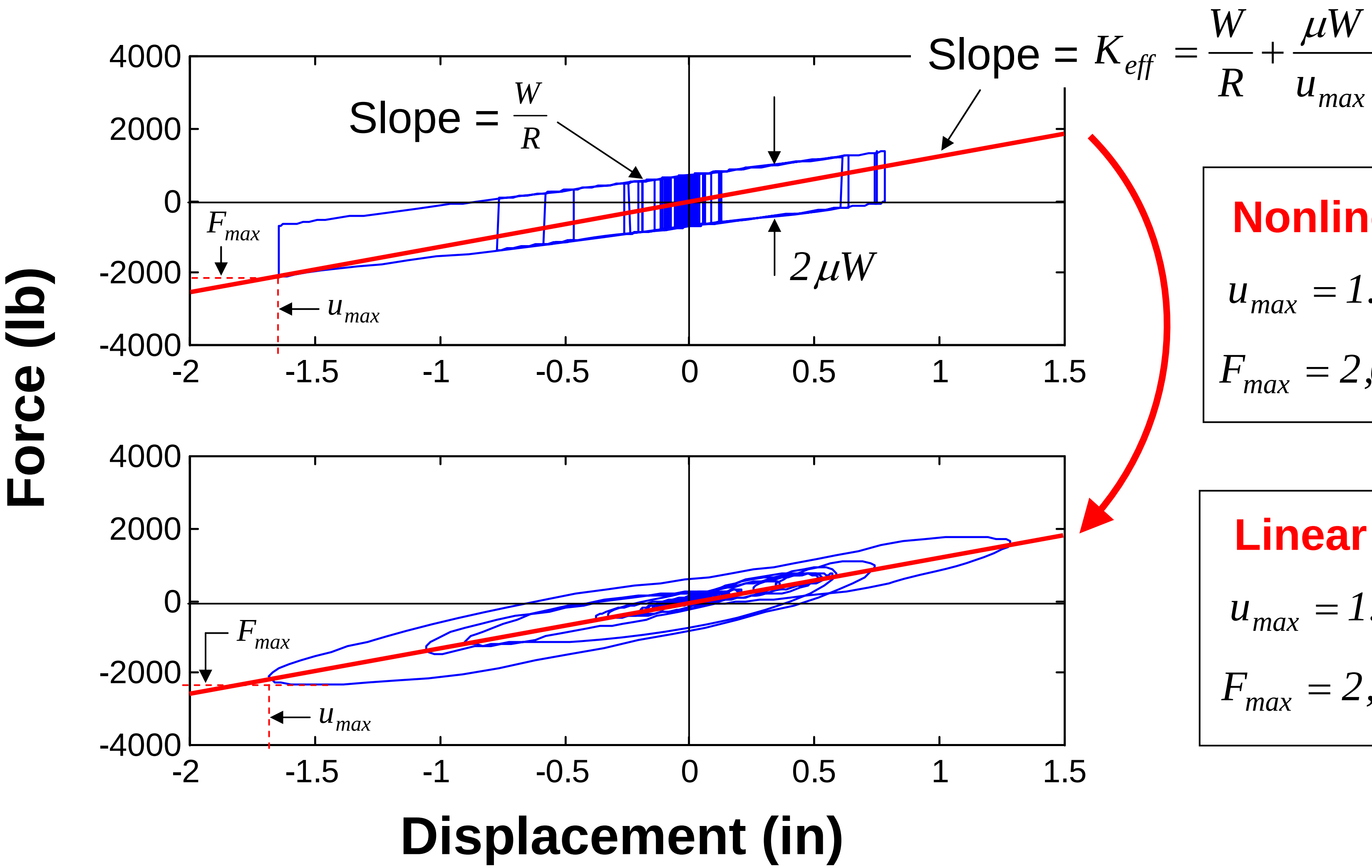


$$K_{eff} = \frac{W}{R} + \frac{\mu W}{u}$$

$$\xi_{eff} = \frac{2\mu R}{\pi(\mu R + u)}$$

$$C_{eff} = 2 m \omega_{n_{eff}} \xi_{eff}$$

Example: Seismic Response Using Nonlinear and Linear Models



Nonlinear

$u_{max} = 1.65\ in.$

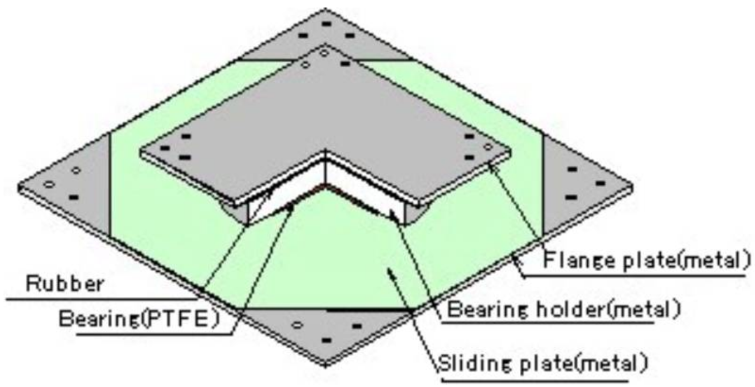
$F_{max} = 2{,}069\ lb$

Linear

$u_{max} = 1.68\ in.$

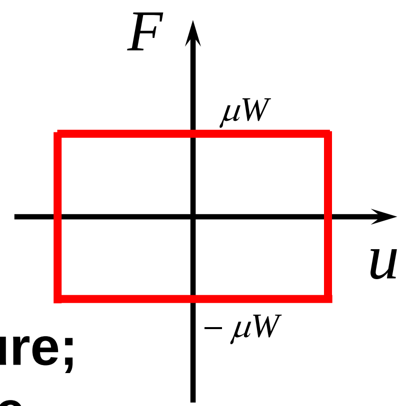
$F_{max} = 2{,}261\ lb$

Flat Sliding Bearings



For Spherical Bearings:

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



- **Flat Bearings:** $R \rightarrow \infty \quad \therefore \; F(t) = \mu W \, sgn(\dot{u})$

- **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**

Examples of Computer Software for Analysis of Base-Isolated Structures

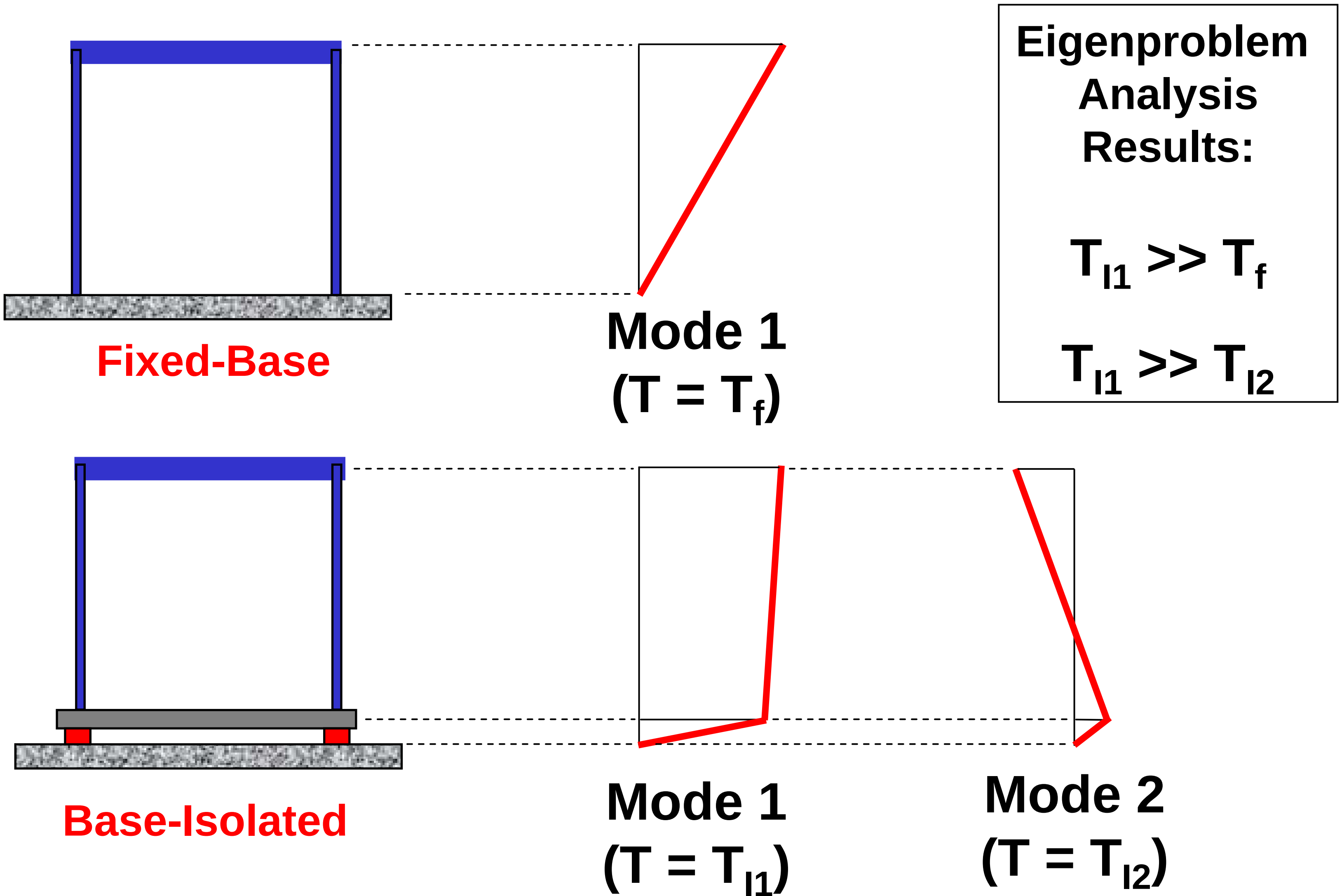
- **ETABS**
  Linear and nonlinear analysis of buildings

- **SAP2000**
  General purpose linear and nonlinear analysis

- **DRAIN-2D**
  Two-dimensional nonlinear analysis

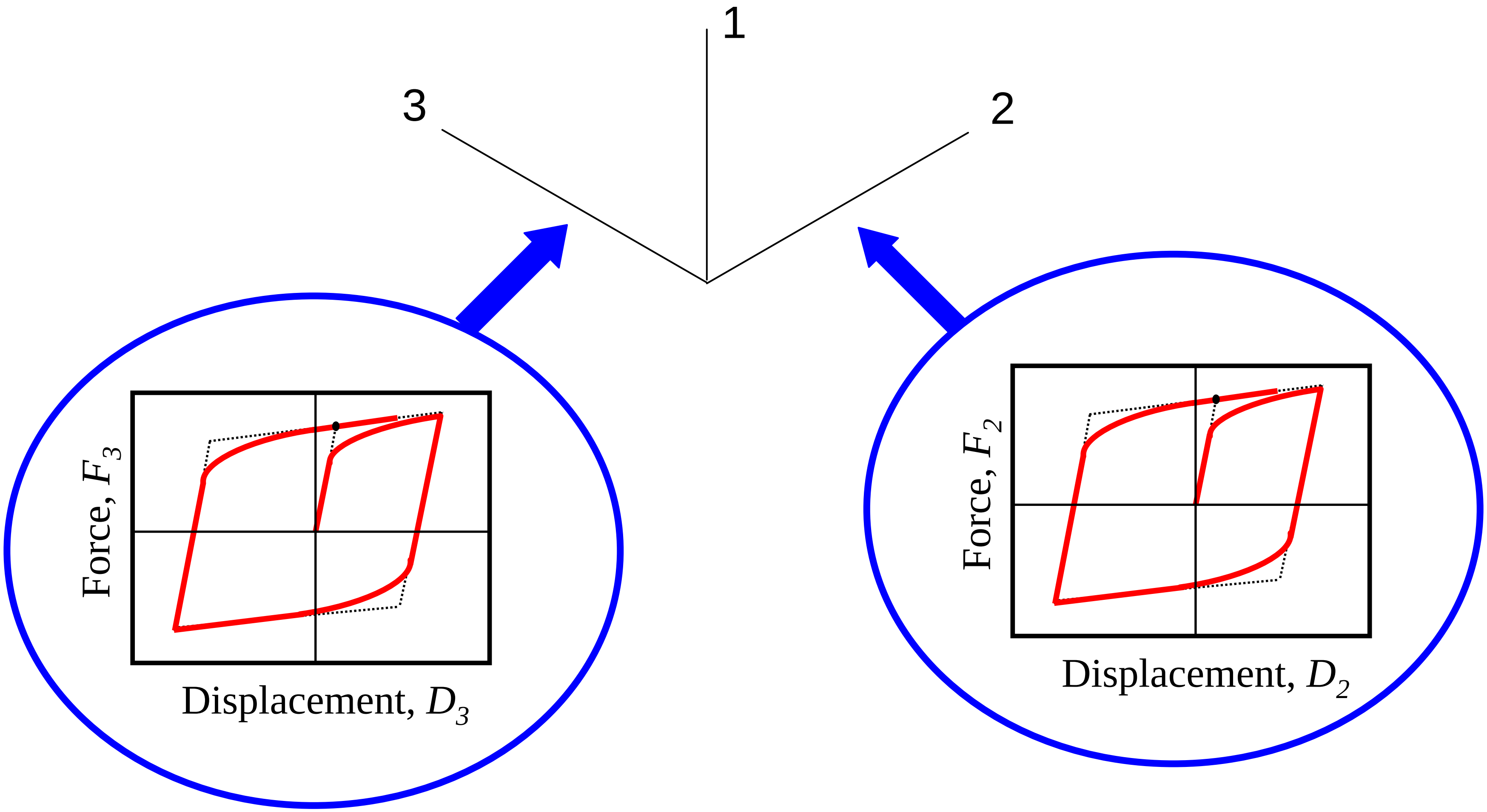
- **3D-BASIS**
  Analysis of base-isolated buildings

Simplified Evaluation of Dynamic Behavior of Base-Isolated Structures



Modeling Isolation Bearings Using the SAP2000 NLLINK Element

ISOLATOR1 Property – Biaxial Hysteretic Isolator



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

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

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

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

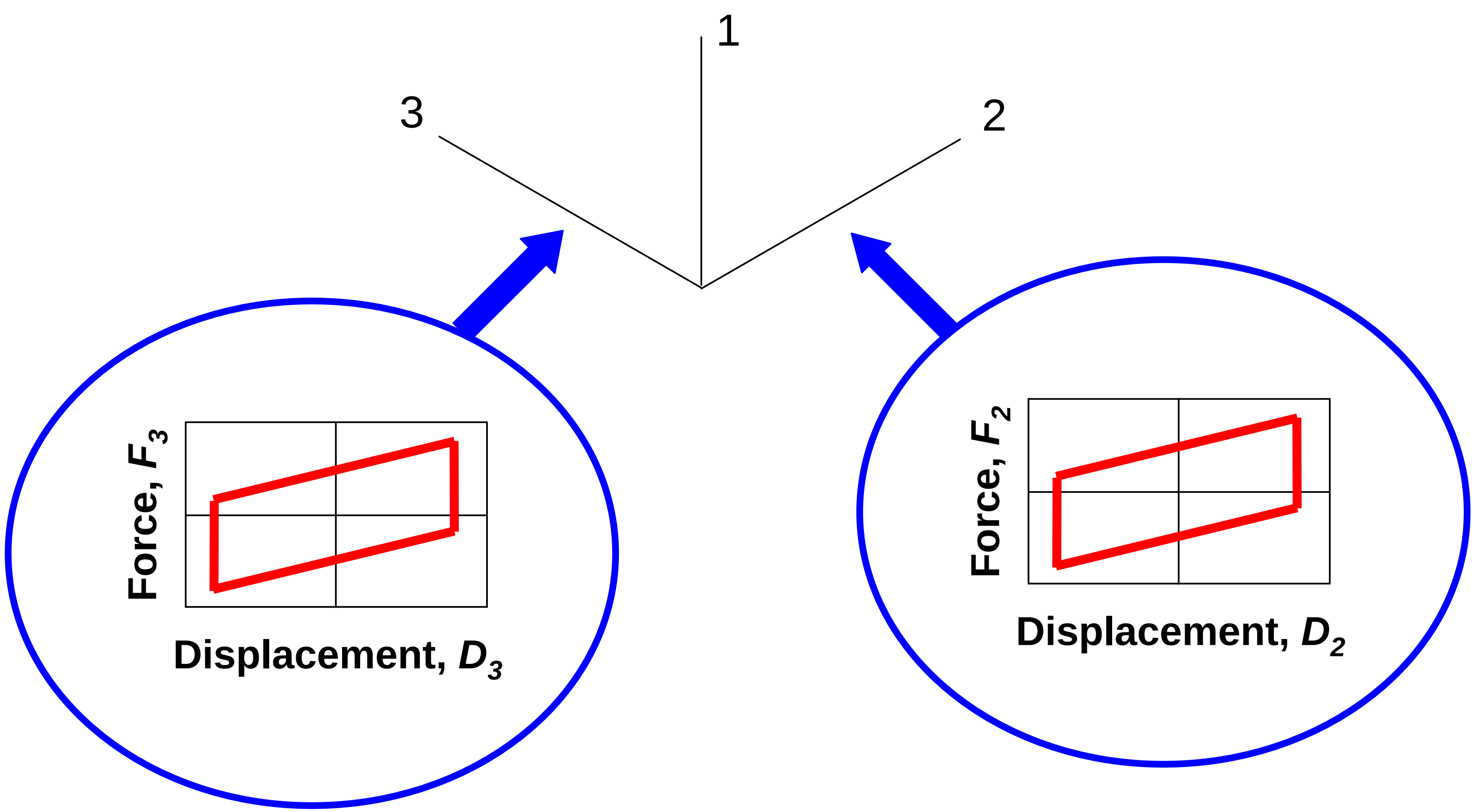
Range of Evolutionary Variables

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

Defines Yield Surface

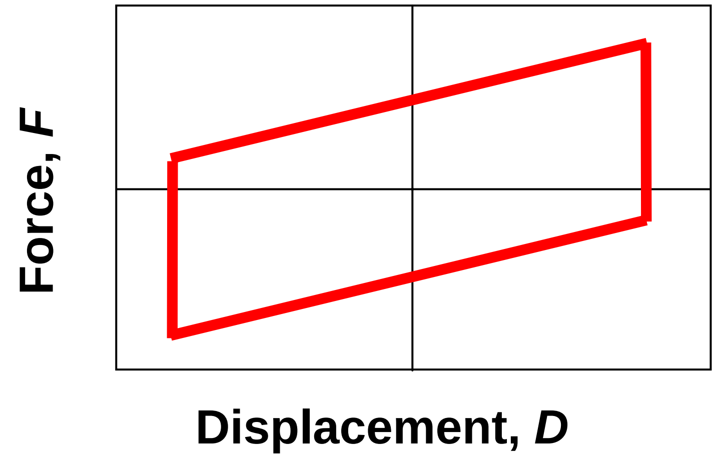
Modeling Isolation Bearings Using the SAP2000 NLLINK Element

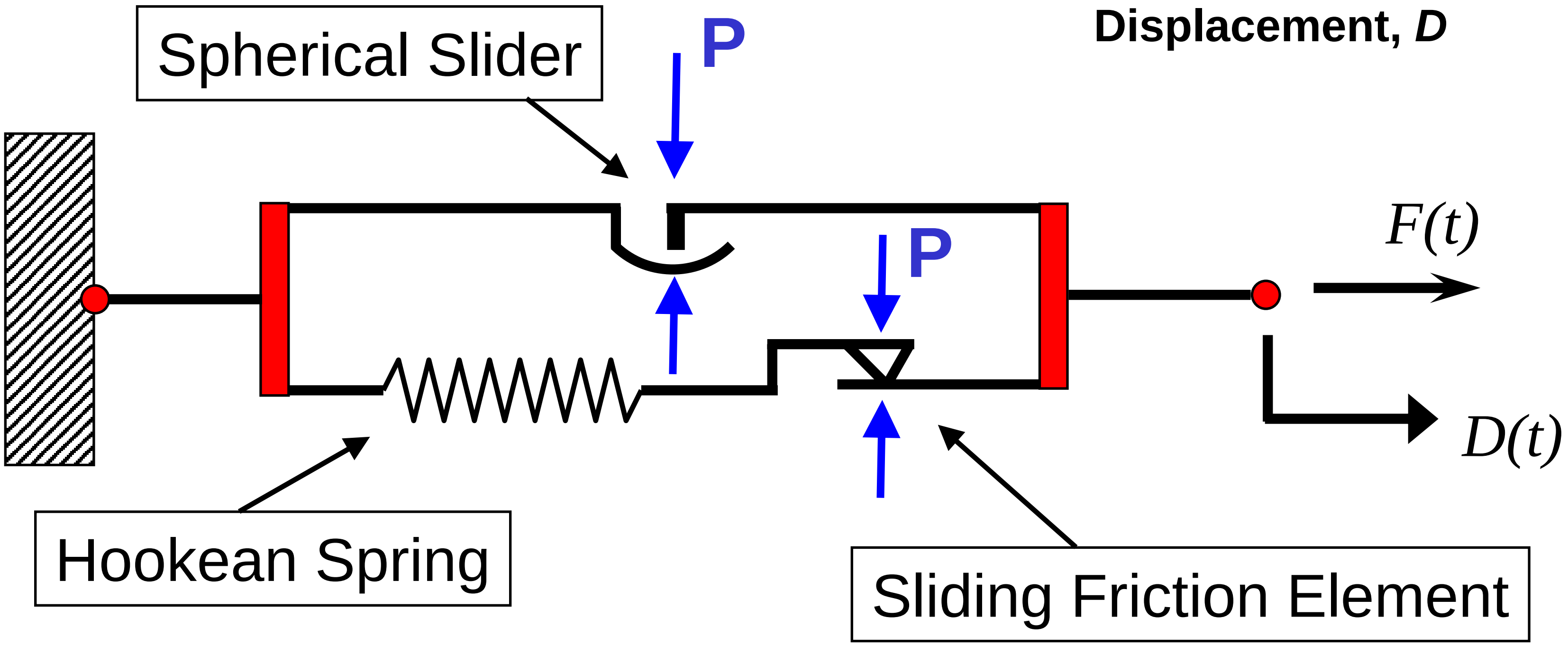
ISOLATOR2 Property – Biaxial Friction Pendulum Isolator



Mechanical Model of FPS Bearing in SAP2000

ISOLATOR2 Property
– Biaxial Friction Pendulum Isolator

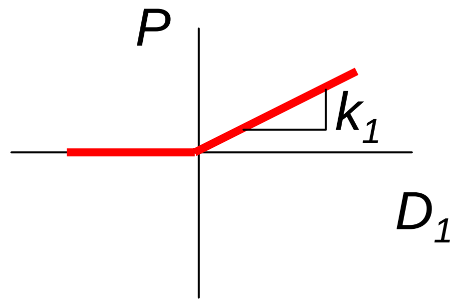




Forces in Biaxial FPS Isolator

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

Axial Force:
+ = Comp.
- = Tension



$$F_2 = \frac{P}{R_2} D_2 + P\mu_2 Z_2$$

$$F_3 = \frac{P}{R_3} D_3 + P\mu_3 Z_3$$

Shear Force Along Each Orthogonal Direction

For FPS Bearing, $R_2 = R_3$

$$\mu_2 = \mu_{max\,2} - (\mu_{max\,2} - \mu_{min\,2})e^{-rv}$$

$$\mu_3 = \mu_{max\,3} - (\mu_{max\,3} - \mu_{min\,3})e^{-rv}$$

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

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

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

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

Range of Evolutionary Variables

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

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

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.

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**

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**

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**

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

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**

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

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)**

Isolation System Displacement (Translation Only)

Design Displacement

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

Design Spectral Acceleration at One-Second Period (g)

Effective Period of Isolated Structure at Design Displacement

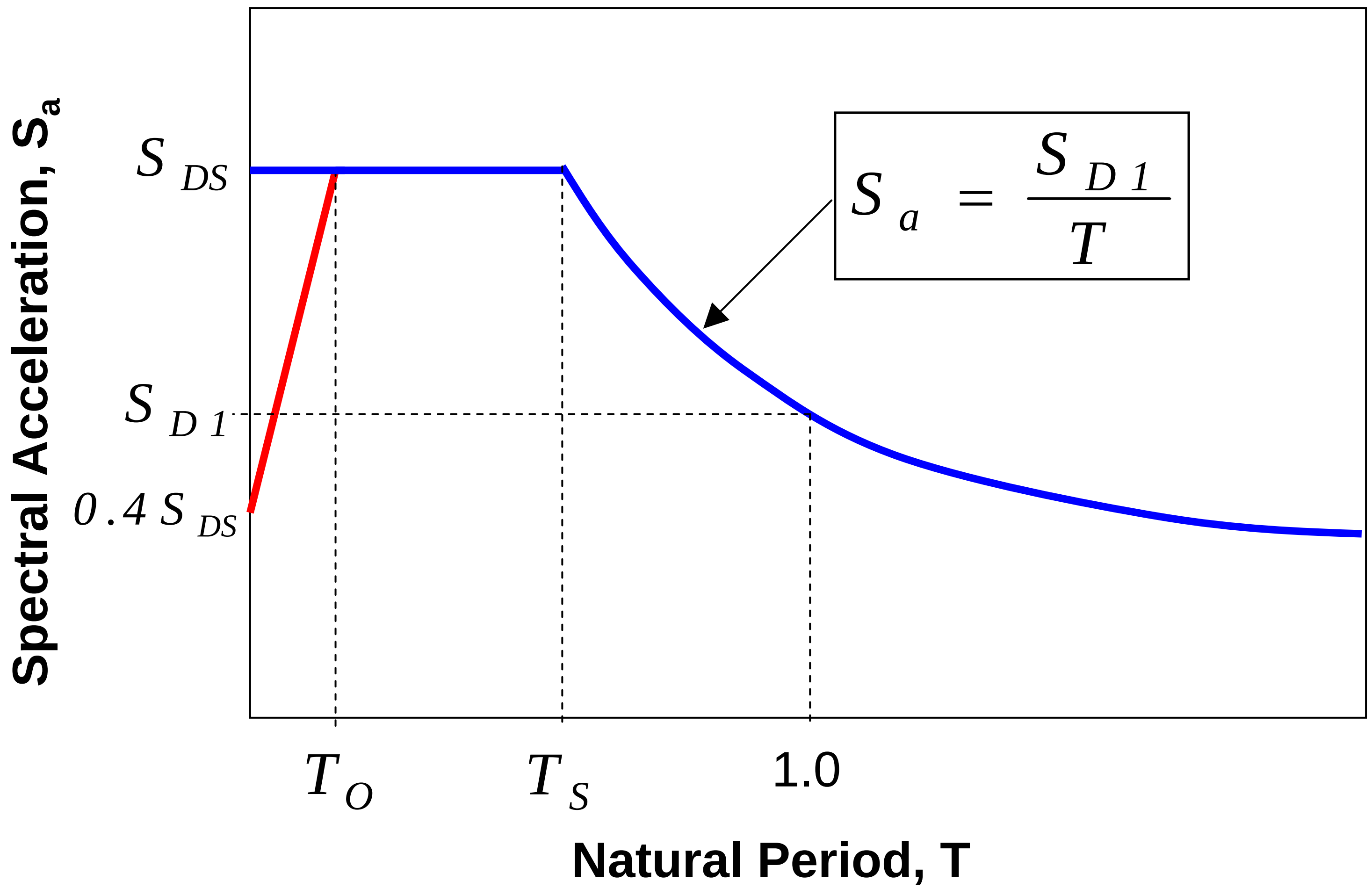
Damping Reduction Factor for Isolation System at Design Displacement

Design is evaluated at two levels:

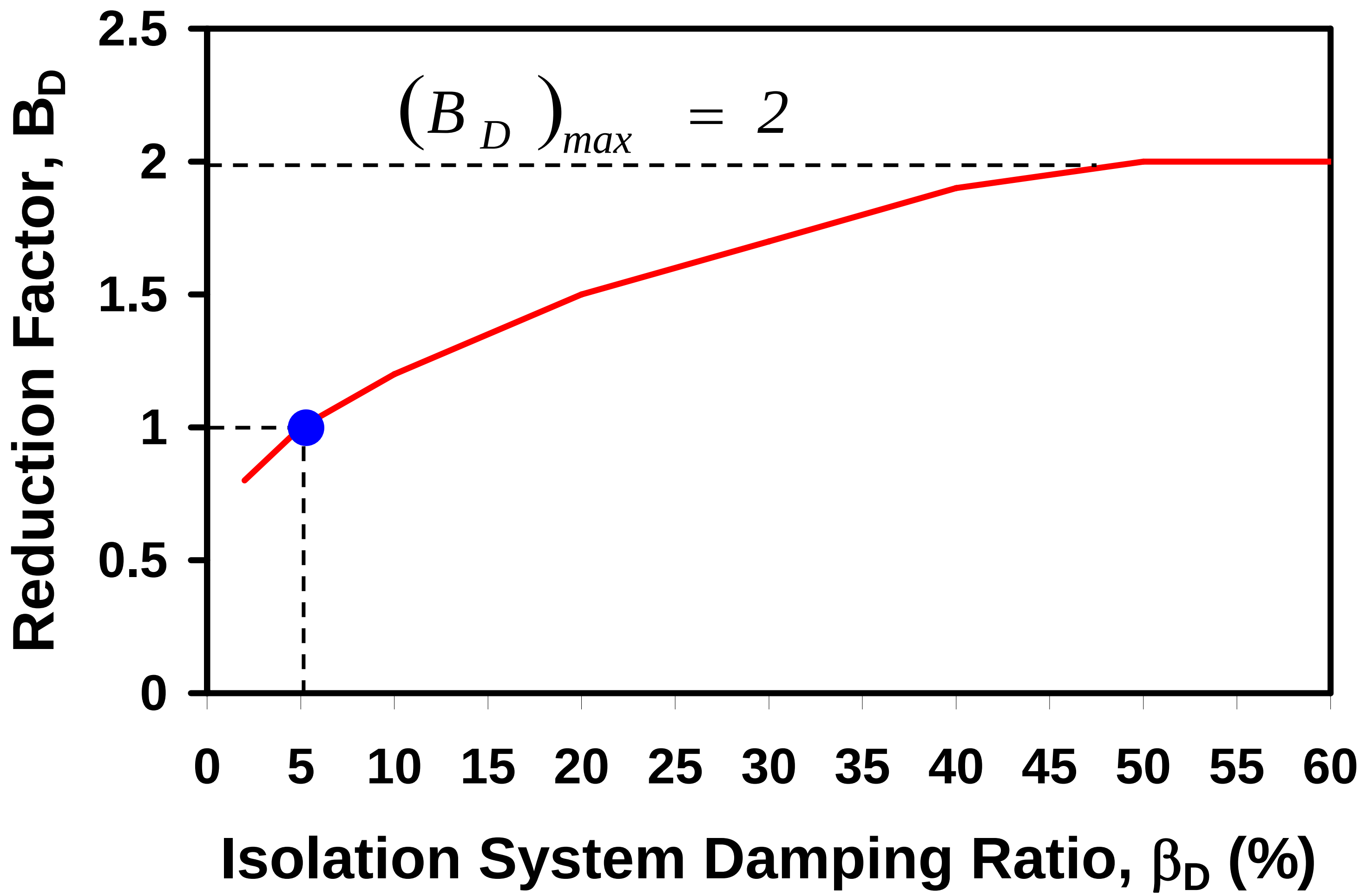
Design Earthquake: 10% / 50 yr = 475-yr return period

Maximum Considered Earthquake: 2% / 50 yr = 2,500-yr return period

Design Response Spectrum



Damping Reduction Factor



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.

Isolation System Displacement (Translation and Rotation)

Total Design Displacement

Eccentricity (actual + accidental) Between CM of Superstructure and CR of Isolation System

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

Use only if isolation system has uniform spatial distribution of lateral stiffness

Distance Between CR of Isolation System and Element of Interest

Shortest and Longest Plan Dimensions of Building

Note: A smaller total design displacement may be used (but not less than $1.1D_D$) provided that the isolation system can be shown to resist torsion accordingly.

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

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

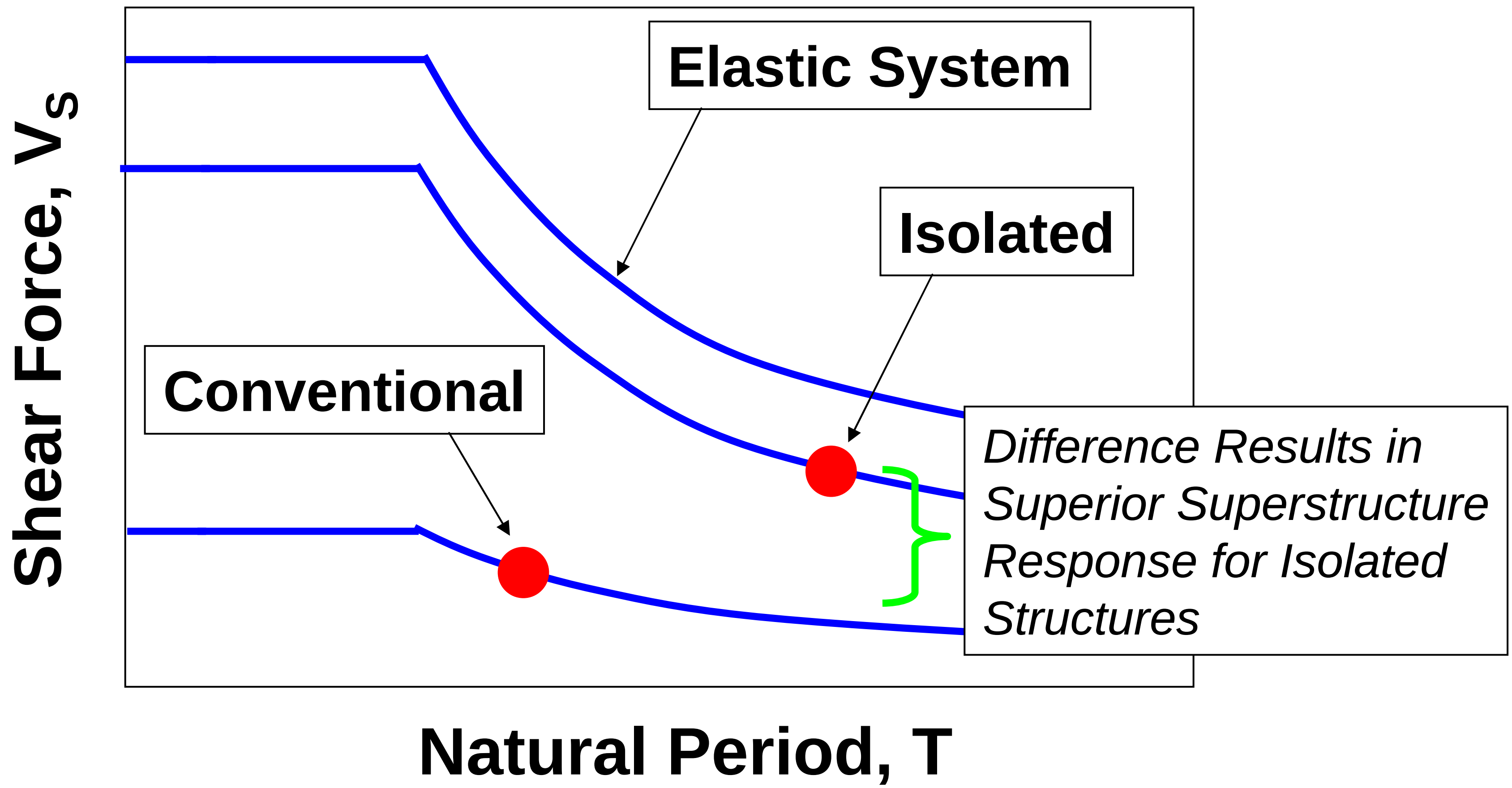
$$R_I = \frac{3}{8} R = \frac{R}{2.67} \leq 2$$

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.

Design Shear Force for Conventional and Isolated Structures



Example: Evaluation of Design Shear Force

Base Shear Coefficient

$$BSC_I = \frac{V_S}{W} = \frac{k_{Dmax} D_D}{W R_I} = \frac{S_{D1}}{B_D R_I T_D}$$

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

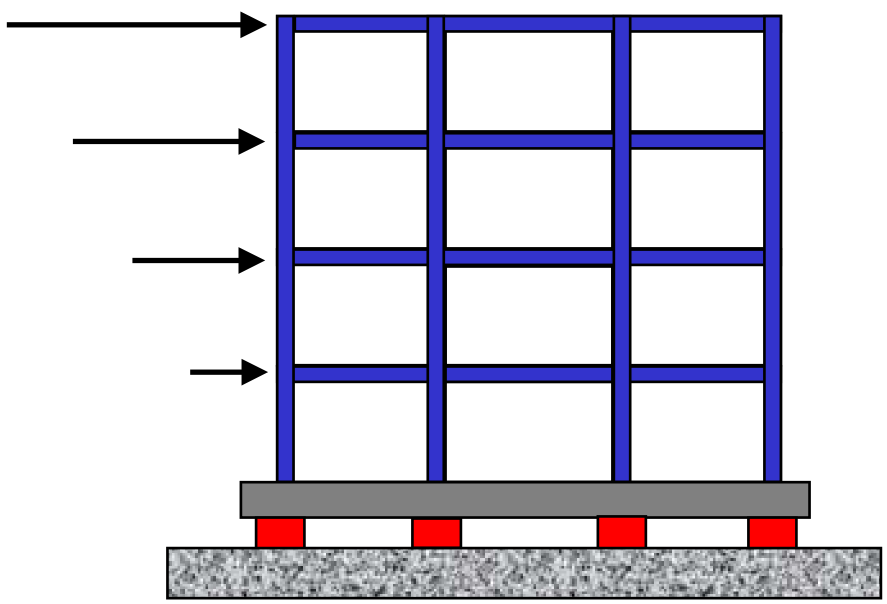
Isolating structure results in 18% *increase* in shear force for design of superstructure

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



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

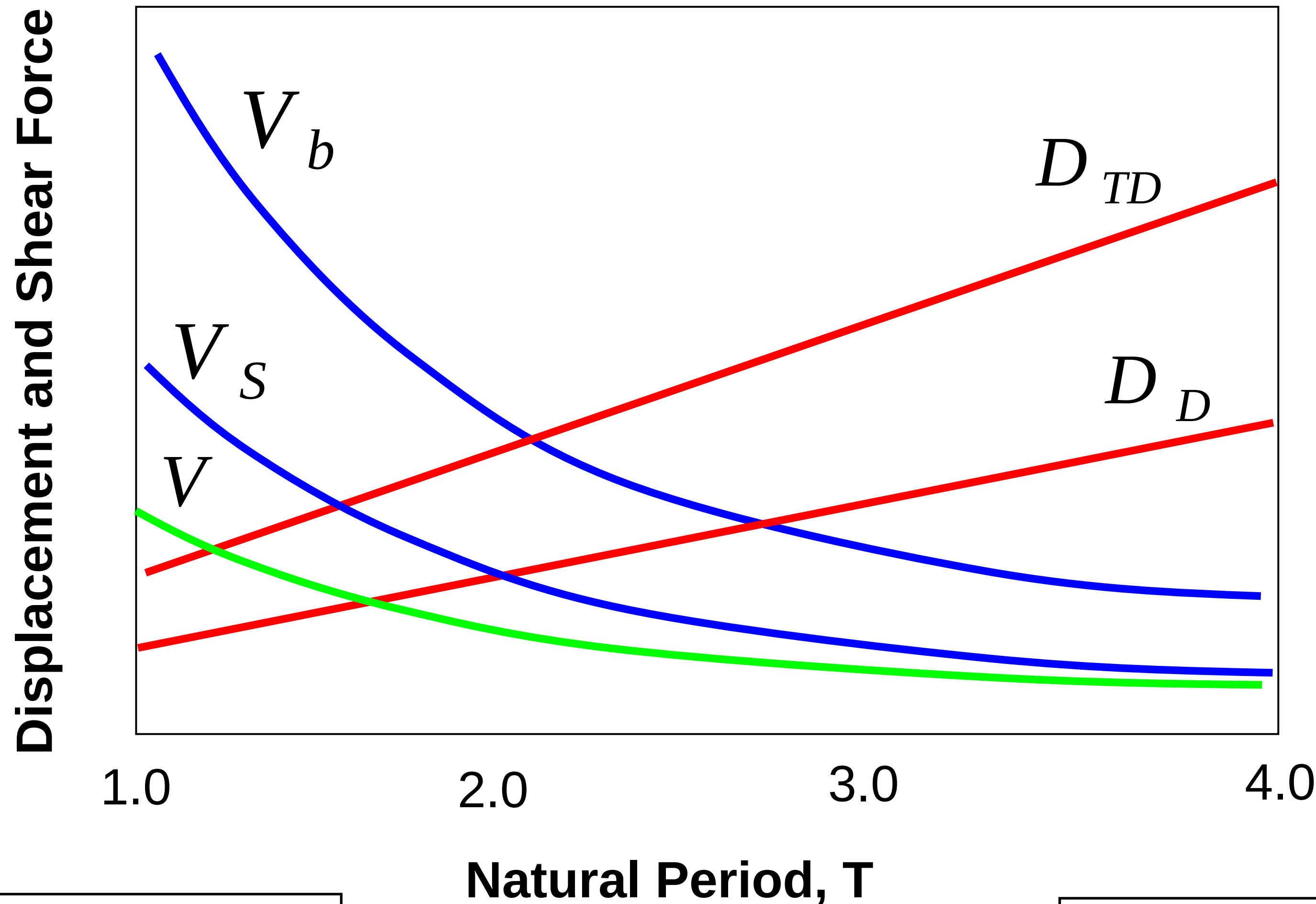
Note: For Isolated Structures, C_d is replaced by R_I.

Interstory Drift of Story x

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

Height of Story x

Displacement and Shear Force Design Spectrum



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

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

$$V = C_S W$$

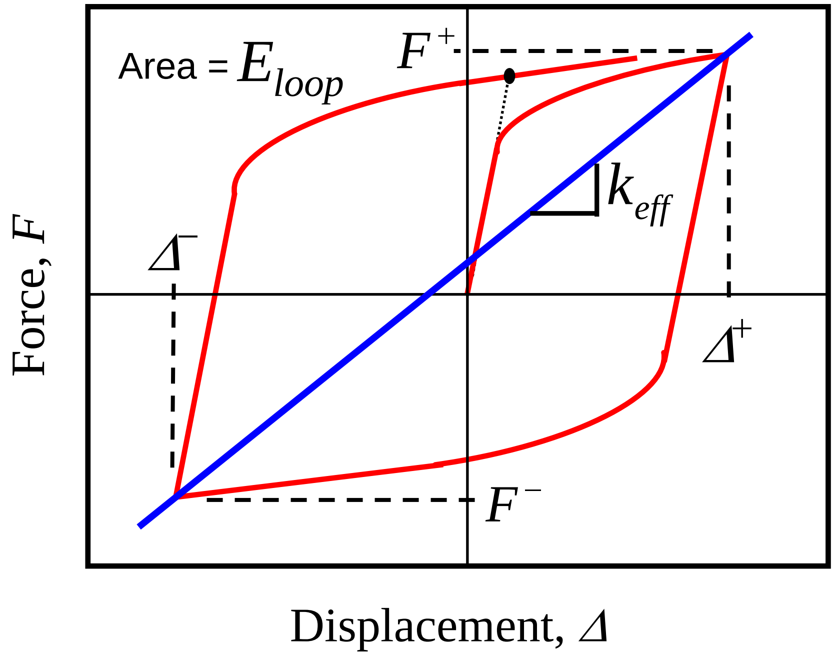
Required Tests of Isolation System

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

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

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

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**

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