NONLINEAR DYNAMIC ANALYSIS OF BASE ISOLATED STRUCTURES: AN OVERVIEW

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Contents

Summary

This chapter presents a brief overview of the analytical modeling techniques used in the nonlinear dynamic analysis of base isolated structures. The localized nonlinearities at the base allow condensation of the linear superstructure to a small number of master degrees of freedom. All the nonlinear bearings and devices are explicitly modeled. Mechanical properties of isolation bearings are described in detail. Material, friction, geometric and contact nonlinearities in the isolation system are discussed. Analytical models used for characterizing the behavior of isolation bearings and devices are presented. Formulation of the combined linear superstructure and nonlinear isolation

system and solution procedure is presented. Computer programs that are most popularly used are described briefly.

1. Introduction

Base isolation involves the introduction of isolation bearings and energy dissipating devices between the superstructure and its foundation. The laterally flexible isolation system shifts the fundamental period—considering an equivalent linear isolation system—of the structure beyond its fixed base period and the predominant periods of the ground motion. The period lengthening to typically 2 to 4 sec is sufficient to reflect the earthquake energy. Energy dissipation in the isolation system is then useful in limiting the displacement response. The isolation bearings generally exhibit material nonlinearities and under certain conditions may also exhibit geometric nonlinearities. However, these nonlinearities are restricted to the isolation system. The superstructure is typically designed to exhibit elastic behavior.

2. Base Isolation Systems

Base isolation systems have gained wide acceptance (Buckle and Mayes 1990, Kelly 1997; Skinner et al. 1993; Soong and Constantinou 1994). The isolation bearings are typically connected between columns and foundation as shown in Figure 1. The isolation system is designed to be very stiff in the vertical direction. The isolation system is designed to provide adequate initial stiffness under service loads, such as wind load, and to provide greater flexibility past yielding of the isolation bearings under strong ground motion or seismic loads.

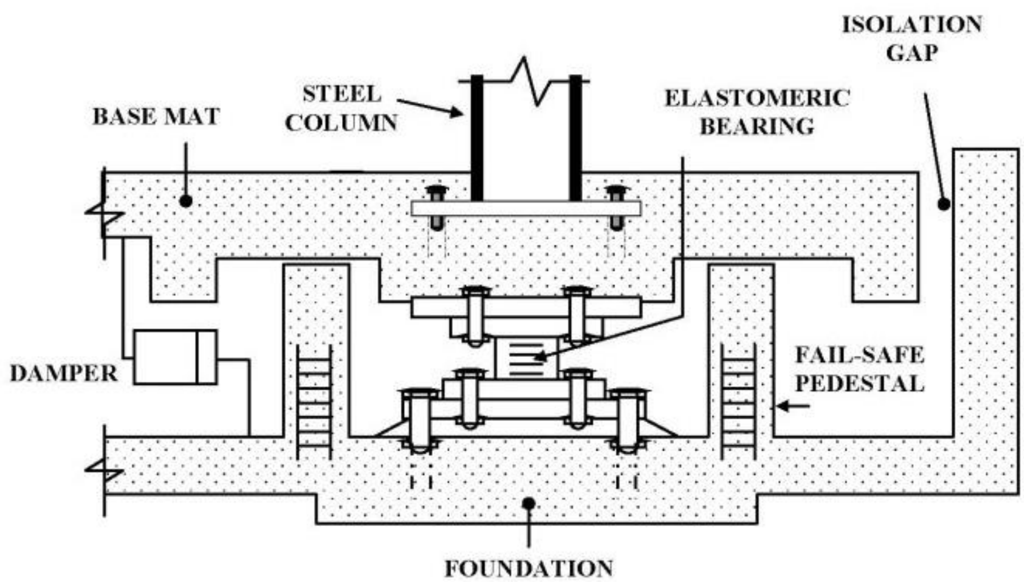

Figure 1. Isolation system details including elastomeric bearing and damper

There are two basic types of isolation bearings: elastomeric bearings and sliding bearings. Elastomeric bearings consist of laminated rubber layers and steel shim plates. Two types of elastomeric bearings that have been implemented in structures are the high damping rubber bearing and the lead rubber bearing. In both types the laminated rubber provides the lateral flexibility. The isolation system level displacements increase due to the lateral flexibility. Adding energy dissipation capacity reduces the isolation system displacements. The energy dissipation capacity is provided by the inherent damping capacity of the rubber in high damping bearings. In lead-rubber bearings, which are typically manufactured with low damping rubber, the cylindrical lead plug within the rubber unit provides the energy dissipation capacity. Moreover, supplemental energy dissipating devices, primarily in the form of fluid viscous dampers, have been used in isolation systems to substantially enhance damping in applications in areas of very high seismicity.

Sliding bearings consist of Teflon or similar materials sliding on a stainless steel surface. Two types of sliding bearings that have been implemented in structures are the Friction Pendulum Sliding (FPS) bearings, spherically shaped sliding bearings, and the flat sliding bearings. Sliding bearings dissipate energy due to friction. Restoring force is provided by the spherical sliding surface in the FPS system or by added springs in the system with flat sliding bearings.

3. Material/Friction Nonlinearities of Base Isolation Bearings and Devices

3.1. Elastomeric Bearings

Elastomeric bearings are typically made of natural rubber and are classified into low damping and high damping bearings. The low damping bearings exhibit shear stiffness which is effectively linear to large shear strains (>100%). The damping is in the range of 2 to 5 % of critical. Lead-rubber bearings are made up of low damping natural rubber with a lead core. The lead core is provided to increase the energy dissipation capacity to about 20 to 30% of critical. The idealized force displacement behavior of a lead-rubber bearing can be characterized as bilinear hysteretic as shown in Figure 2. The high initial stiffness offers rigidity under wind load and low level seismic load. The characteristic strength, $Q = A_{\mathrm{p}}\sigma_{\mathrm{YL}}$, where A_{p} is the lead plug area and σ_{YL} is the effective shear yield stress of lead. The post yielding stiffness, K_{p}, is typically higher than the shear stiffness of the bearing without the lead core:

$$K_{\mathrm{p}} = \frac{A_{\mathrm{r}}G}{\sum t} f \, , \qquad (1)$$

where A_{r} is the bonded rubber area, Σt is the total rubber thickness, G is the shear modulus of rubber, and f is a factor larger than unity. Under proper conditions, f, may be equal to or less than 1.15. Moreover, the initial elastic stiffness, K_{e}, ranges between 6.5 to 10 times the post-yielding stiffness.

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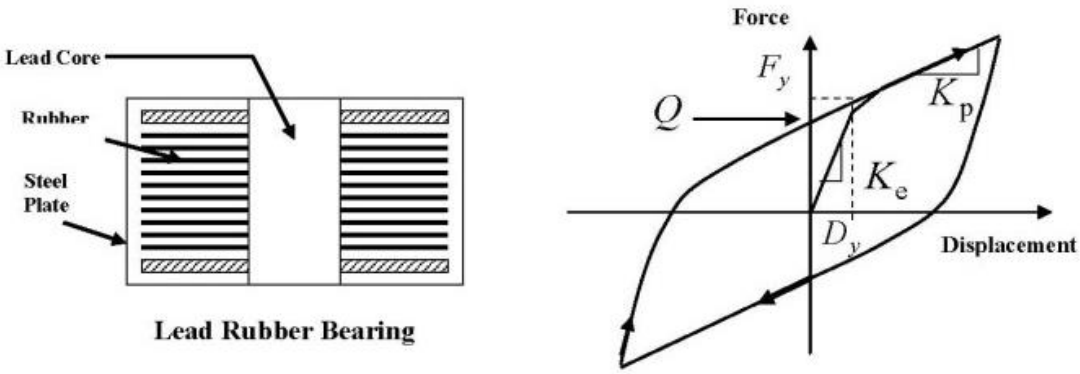

Figure 2. Lead rubber bearing: bilinear force-displacement loop

The stiffness and energy dissipation characteristics of high damping bearings are highly nonlinear and dependent on shear strain as shown in Figure 3. The high damping bearings are made up of specially compounded rubber, which provides effective damping of 10 to 15 % of critical. The high damping bearings have high shear stiffness at low shear strains (< 20%) for rigidity under wind load and low level seismic load. The shear stiffness is typically lower in the range of 20 to 120 % shear strains. At large shear strains, the shear stiffness increases due to strain crystallization process in the rubber. The damping in high damping bearings is best characterized by a combination of hysteretic and viscous behavior. In the virgin stage and during the first cycle of movement, the bearings exhibit higher stiffness and damping than in the following cycles. The stiffness stabilizes by the third cycle, resulting in stable properties termed as scragged properties. Scragging of the bearings is the result of internal changes in the rubber. Recovery to the unscragged (virgin) properties occurs following sufficient time. The scragged state of the bearings can be modeled by a bilinear hysteretic model for shear strains of up to 200%. The stiffening behavior (see Figure 3) beyond this strain can also be modeled using more complex models (Constantinou et al. 2007, Tsopelas et al. 1994, Kikuchi and Aiken 1997). The current technique used to model high damping bearings is to perform multiple analyses with bilinear hysteretic models; the parameters of the bilinear hysteretic models are determined at specific shear strain amplitudes. The bilinear model parameters can be established from test data of prototype bearings. These properties are the shear modulus, G, and the equivalent damping ratio, ξ (defined as the energy dissipated in a cycle of motion divided by 4π and by the maximum kinetic energy) under scragged conditions. G, is related to the post yielding stiffness K_{p}':

$$K_{\mathrm{p}}' = \frac{GA_{\mathrm{r}}}{\Sigma t}. \tag{2}$$

The parameters of the model may be determined by use of the mechanical properties of G and ξ at a specific strain—for example, parameters corresponding to the design displacement. The post yielding stiffness, K_{p}', is determined from (2), whereas the characteristic strength, Q, may be related to the mechanical properties by assuming bilinear hysteretic behavior:

$$Q = \frac{\pi\ \xi\ K_{\mathrm{p}}' D^2}{(2-\pi\ \xi)D - 2D_y}, \tag{3}$$

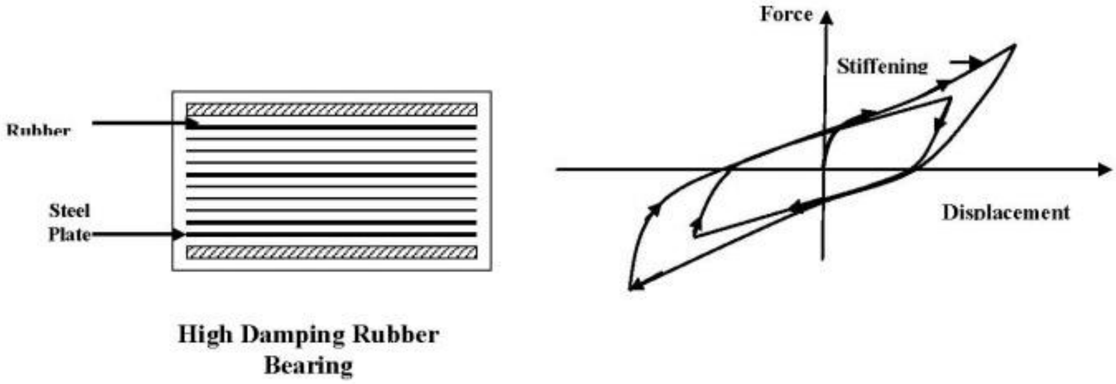

Figure 3. High damping bearing: force displacement loop with stiffening

where the yield displacement, D_y , is between 0.05 and 0.1 times the total rubber thickness and D is the design displacement. The yield force, F_y , is given by

$$F_y = Q + K_{\mathrm{p}}' D_y. \tag{4}$$

And the post to pre-yielding stiffness ratio is given by

$$\alpha = \frac{K_{\mathrm{p}}' D_y}{F_y}. \tag{5}$$

Elastomeric bearings have finite vertical stiffness that affects the vertical response of the isolated structure. The vertical stiffness of an elastomeric bearing can be estimated as follows

$$k_{\mathrm{v}} = \frac{E_{\mathrm{c}} A_{\mathrm{r}}}{\Sigma t}, \tag{6}$$

where E_{c} is the compression modulus.

3.2. Sliding Bearings

Two types of sliding bearings are the flat sliding bearings with restoring force devices and the friction pendulum bearings (FPS) shown in Figure 4. Flat sliding bearing is made up of Teflon sliding on a flat stainless steel surface. The re-centering capability is provided by additional elastic springs. The FPS bearing, shown in Figure 4, is made up of a composite material sliding on a spherical surface with radius of curvature R, which provides the re-centering force. The behavior of FPS bearing can be represented by

$$F = \frac{N}{R}U + \mu_s N \operatorname{sgn}(\dot{U}). \tag{7}$$

where F is the force in the bearing, U and $\dot{U}$ are the displacement and velocity, respectively, μ_s is the coefficient of sliding friction (dependent on velocity and pressure) and N is the normal load on the bearing. It should be noted that for flat sliding bearings R is infinite. The coefficient of friction of sliding bearings depends on a number of parameters of which the composition of the sliding interface, bearing pressure and velocity of sliding (as shown in Figure 5) are the most important. For interfaces consisting of polished stainless steel in contact with Teflon or composites the coefficient of friction may be described by (Constantinou et al. 1990)

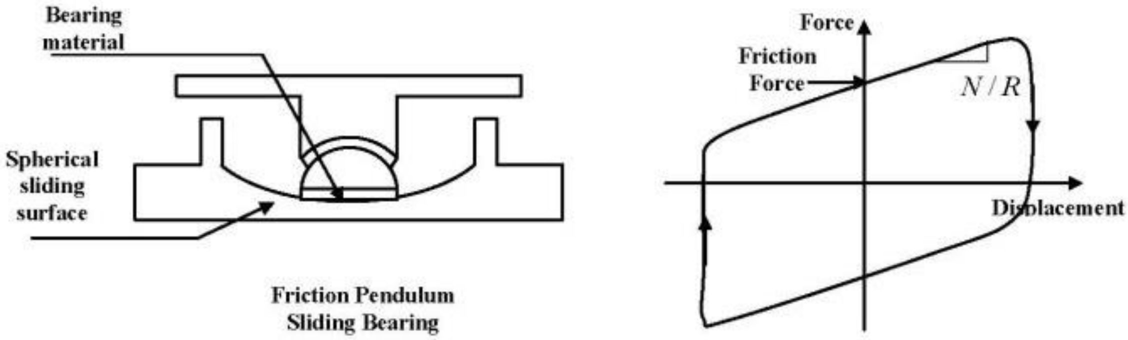

Figure 4. Friction pendulum bearing: force-displacement loop (includes friction and re-centering force)

$$\mu_s = f_{max} - (f_{max} - f_{min})\exp\left(-a|\dot{U}|\right), \tag{8}$$

where the parameters f_{min} and f_{max} describe, respectively, the coefficients of friction at essentially zero and large velocities of sliding and under constant pressure. Parameters f_{min}, f_{max} and a depend on the bearing pressure, although only the dependency of f_{max} on pressure is of practical significance.

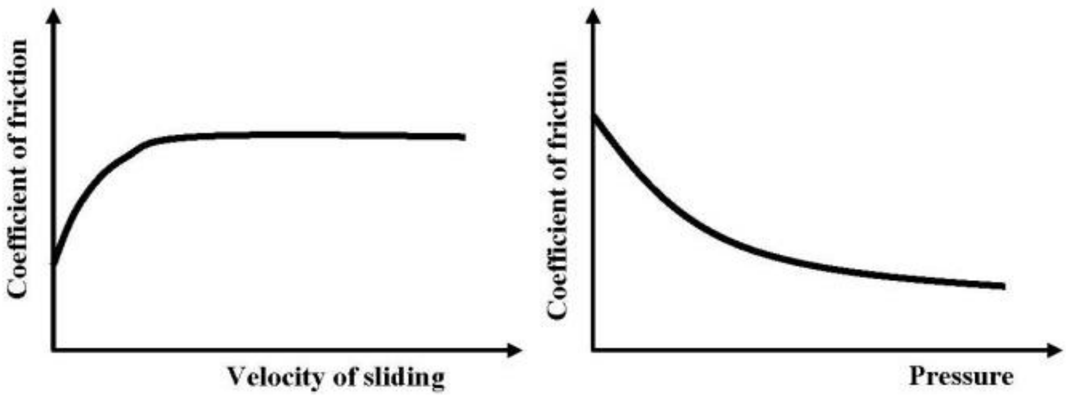

Figure 5. Variation of friction coefficient as a function of sliding velocity and pressure

More recently Fenz and Constantinou (2008), Morgan and Mahin (2011), Ray and Reinhorn (2012) and Dao et al. (2013) have studied the triple friction pendulum isolation bearing that has an inner slider and articulated sliders sliding inside concave sliding surfaces as shown in Figure 6, and developed detailed analytical models with force-displacement behavior as shown in Figure 7.

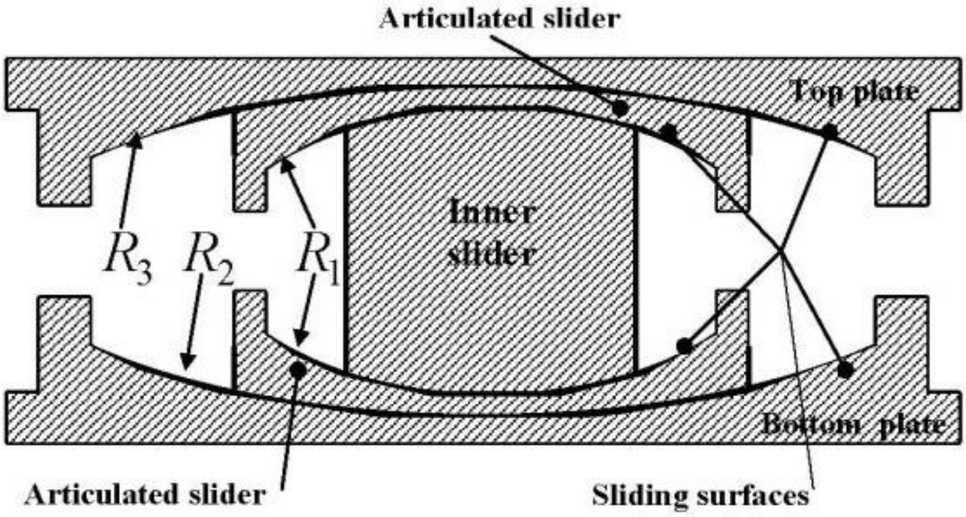

Figure 6. Triple Friction Pendulum Isolator

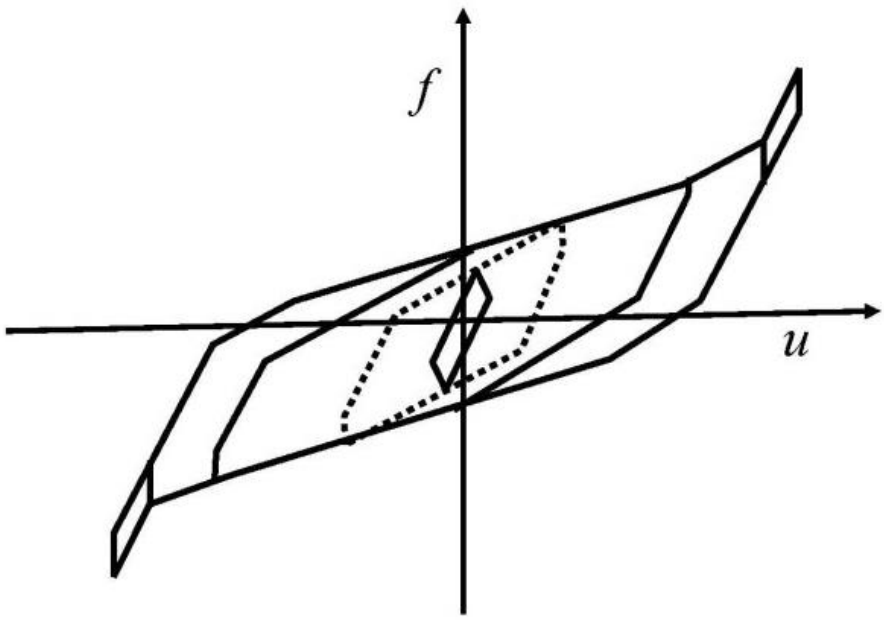

Figure 7. Force (f) - Displacement (u) Behavior of Triple Friction Pendulum Isolator

3.3. Fluid Viscous Dampers

Fluid dampers (Constantinou 1993) are used to enhance the damping in the isolation system and are connected between the base and foundation as previously shown in Figure 1. Fluid viscous dampers produce force by forcing fluid (typically silicone oil)

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through orifice passages as shown in Figure 8. It is possible to shape the orifice passages (Constantinou 1993) in such a way as to produce an output force of the type

$$F = C \left| \dot{U} \right|^{\alpha} \mathrm{sgn}(\dot{U}), \tag{9}$$

where C = damping coefficient, α is in the range of 0.5 to 1.0 and the representative force-displacement loops are shown in Figure 8.

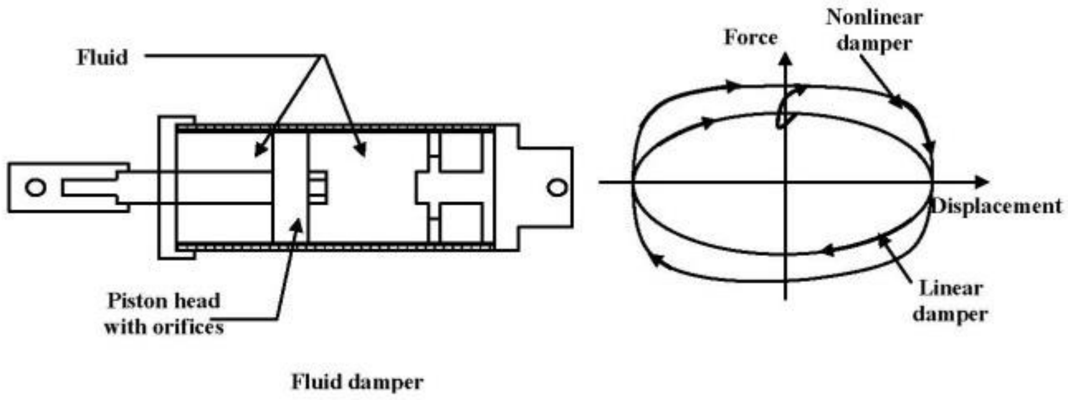

Figure 8. Fluid Damper: force displacement loop (Velocity Dependent Damping Force)

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Biographical Sketches

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