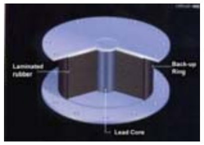
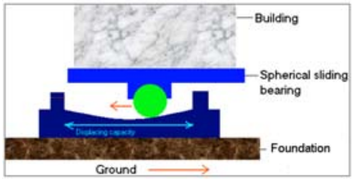
Seismic Isolation & Energy Dissipation Systems

Seismic Isolation Systems

Lead Rubber Bearings

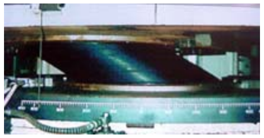


Sliding Systems



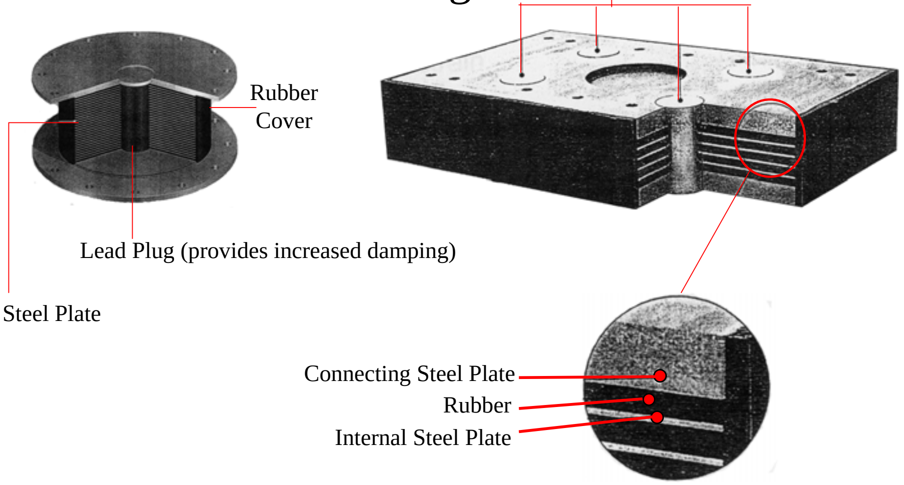
Lead Rubber Bearings

By using Isolators and dampers, the building is "decoupled" from the ground motion of any earthquake and the transmission of seismic energy to the building is dampened. This is done by lowering the vibrational frequency, allowing the building to move or displace, and lowering the shock acceleration of the seismic event thus reducing the tendency for the upper floors to move faster than the lower floors. In general, buildings that have been isolated in this way are subjected to 1/3 to 1/5 of the horizontal acceleration of conventional structures during a seismic event.



http://www.lacityhall.org/isohow.html

Lead Rubber Bearings



Lead Plugs

Rubber Cover

Lead Plug (provides increased damping)

Steel Plate

Connecting Steel Plate

Rubber

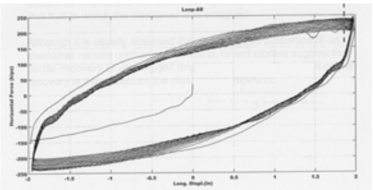
Internal Steel Plate

Steel plates distribute shear forces to the lead core.

Prepared from Dr. Benzoni's SE207 Base Isolation Course Notes

Lead Rubber Bearings

The lead plug increases the damping through the hysteretic shear deformations of the lead.



Advantages of lead are:

1. It yields in shear at low stress levels
2. Lead has good fatique properties during cycling at plastic strain
3. Lead is readily available at high purities (allows properties to be predictable).

The layers of steel plates improve the efficiency of the lead plug as well as the stability of tall bearings under lateral loads

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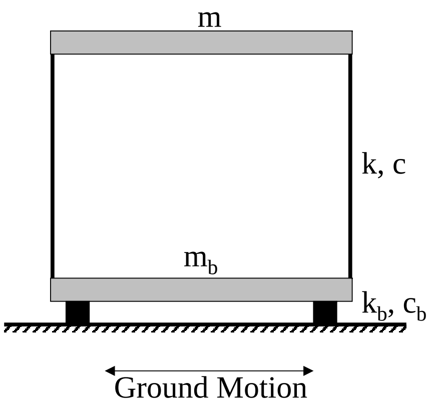
SDOF System with Base Isolation



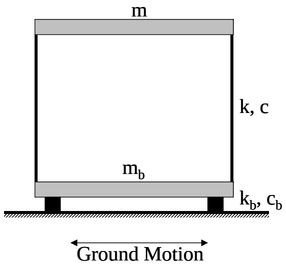
$$\omega_s = \sqrt{\frac{k}{m}}$$

$$\omega_b = \sqrt{\frac{k_b}{m + m_b}}$$

Equation of Motion (Absolute Reference)

$$\begin{bmatrix} m+m_b & 0 \\ 0 & m \end{bmatrix} \begin{Bmatrix} \ddot{x}_b \\ \ddot{x}_s \end{Bmatrix} + \begin{bmatrix} c_b & 0 \\ 0 & c \end{bmatrix} \begin{Bmatrix} \dot{x}_b \\ \dot{x}_s \end{Bmatrix} + \begin{bmatrix} k_b & 0 \\ 0 & k \end{bmatrix} \begin{Bmatrix} x_b \\ x_s \end{Bmatrix} = -\begin{bmatrix} m+m_b & 0 \\ 0 & m \end{bmatrix} \begin{Bmatrix} 1 \\ 0 \end{Bmatrix} \ddot{x}_g$$

2DOF System Properties

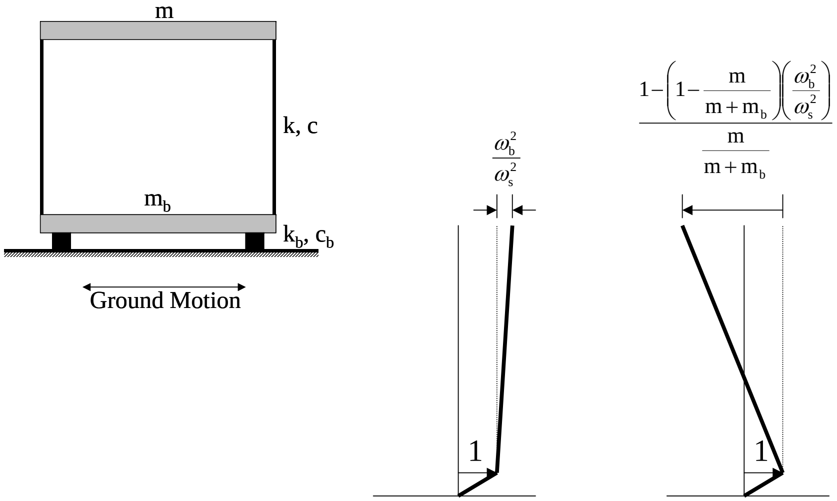


$$\omega_b^* \approx \omega_b$$

$$\omega_s^* \approx \frac{\omega_s}{\sqrt{\left(1 - \frac{m}{m+m_b}\right)}}$$

1. The frequency of the base isolator is only slightly affected by the structure.
2. The frequency of the structure is significantly increased by the addition of the base mass.
3. The separation between isolation frequency and the structure's fixed-base frequency are increased.

Change in Mode Shapes



The first buildings in the U.S. to be outfitted with base isolators were:

- The Law and Justice Center in Rancho Cucamonga, California (1985),
- The Fire Department Command and Control Facility in Los Angeles (1990),
- The University of Southern California Teaching Hospital in east Los Angeles (1991). This last building had a severe test in 1994, when the Northridge earthquake hit. Though it was only 23 miles from the epicenter, the horizontal acceleration in the building was three or four times less than the peak acceleration outside: the building was effectively isolated from the motions that caused significant damage to buildings nearby.

http://www.exploratorium.edu/faultline/engineering/engineering5.html

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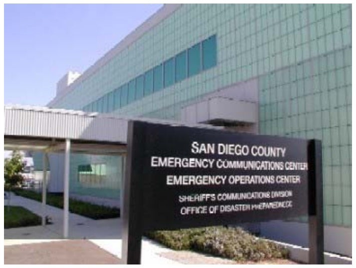
San Diego County Emergency Communications Center



38,000 square foot, two-story, state-of-the-art facility built in 1998 to accommodate the San Diego County Sheriff's Communications Center, and the San Diego County Office of Disaster Preparedness (cost of $5.8 million).

Ability to withstand the destructive forces of an earthquake through the use of 26 base isolators, allowing the building the flexibility to move 14 inches laterally and 10 inches vertically.

http://www.sdsheriff.net/ccweb/building.htm

USC University Hospital

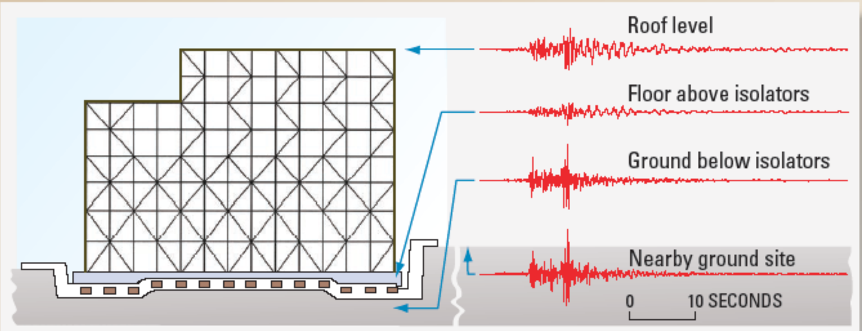


Diagram showing structural cross section of USC University Hospital. Brown rectangles in foundation represent base isolators (see photos below).

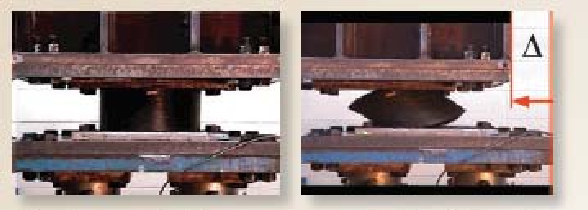
Building response recorded in the 1994 Northridge earthquake.

8-story steel superstructure supported by 149 isolators sitting on continuous concrete footings.

During the 1994 Northridge earthquake, the isolators reduced the accelerations by 66% at the base and 40% at the roof.

http://geopubs.wr.usgs.gov/fact-sheet/fs068-03/fs068-03.pdf

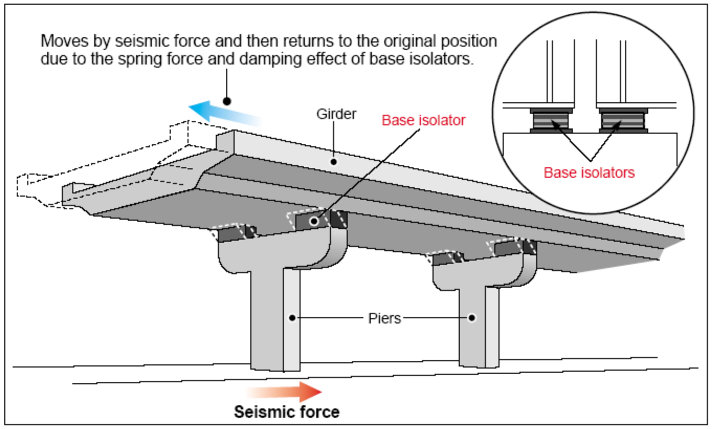
USC University Hospital



Base isolators in laboratory tests—(left) undeformed isolator, (right) deformed isolator with sizeable horizontal displacement (Δ). Such displacement of isolators prevents large displacements of floors of the building above.

http://geopubs.wr.usgs.gov/fact-sheet/fs068-03/fs068-03.pdf

Base Isolators and Bridges

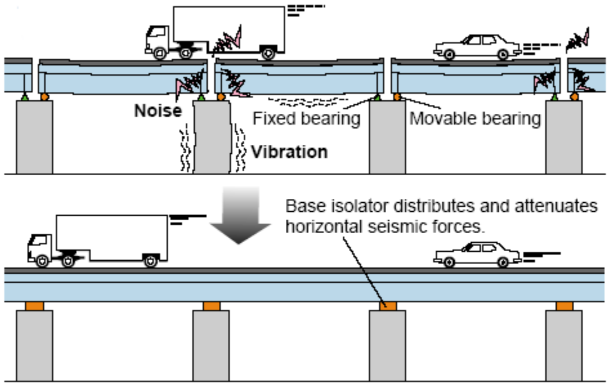


Rubber base isolators are used to replace steel bearings.

These isolators reduce the seismic forces reachings the girders and reaction forces on the piers.

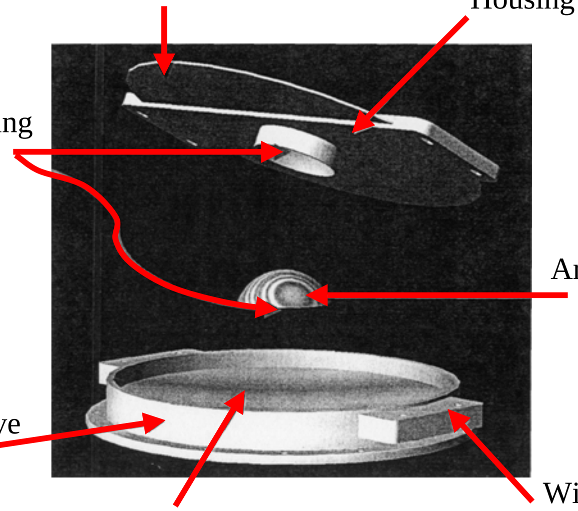
http://www.hepc.go.jp/english/pdf/GHEQ_A.pdf

Removing Joints from Bridges



http://www.hepc.go.jp/english/pdf/GHEQ_A.pdf

Friction Pendulum (Sliding System)



Prepared from Dr. Benzoni's SE207 Base Isolation Course Notes

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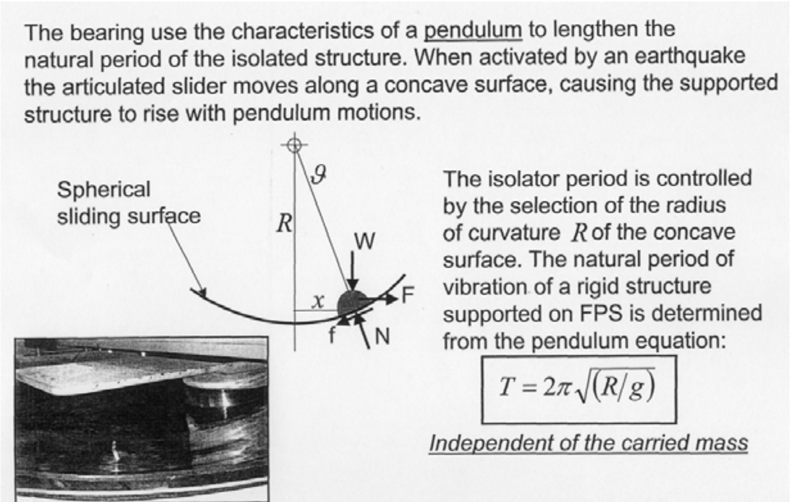
Friction Pendulum - Theory

Relying on energy dissipation at sliding interfaces



The bearing use the characteristics of a pendulum to lengthen the natural period of the isolated structure. When activated by an earthquake the articulated slider moves along a concave surface, causing the supported structure to rise with pendulum motions.

The isolator period is controlled by the selection of the radius of curvature R of the concave surface. The natural period of vibration of a rigid structure supported on FPS is determined from the pendulum equation:

$$\boxed{T = 2\pi\sqrt{(R/g)}}$$

Independent of the carried mass

Prepared from Dr. Benzoni's SE207 Base Isolation Course Notes

Friction Pendulum – Advantages / Disadvantages

Advantages

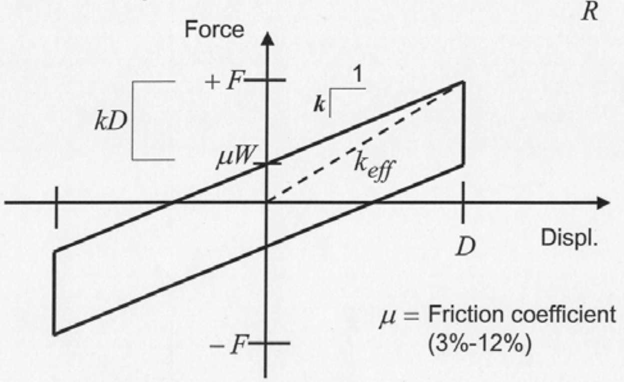
- F.P. systems can accommodate much larger levels of displacements than rubber bearings.
- F.P. systems offer more space efficiency (and are shorter) than rubber bearings with the same displacement capacity.
- By increasing the sliding period, the base shear is reduced and displacements are increased.
- Reducing the coefficient of friction further reduces base shear and increases displacement.
- Offer very predictable performance (particularly over rubber bearings).
- The isolator period is independent of the mass of the supported structure.
- Curvature of the F.P. controls the frequency of the device.

Disadvantages

- These devices are more expensive than rubber bearings (due to construction costs).
- The system offers only some re-centering capabilities.
- There are problems associated with adverse torsional motions in asymmetric structures.
- Can suffer from stick-slip motion and non-uniform pressure distributions on the sliding interfaces.

Friction Pendulum – Energy Dissipation

The lateral restoring stiffness of the FPS is obtained as: $k = \frac{W}{R}$



μ = Friction coefficient (3%-12%)

$$k_{eff} = \frac{F}{D} = \frac{kD+\mu W}{D} = \frac{\frac{W}{R}D+\mu W}{D} = \frac{W}{R}+\frac{\mu W}{D}$$

Examples of Friction Pendulum Systems

http://www.tfhrc.gov/pubrds/04jan/09.htm

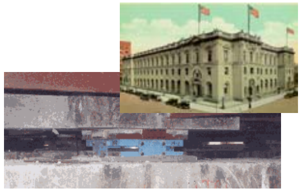
A F.P. installed as part of a seismic retrofit of the Hernando DeSoto Bridge in Memphis, TN.

http://www.djc.com/news/co/11134804.html

F.P. system installed on the roof of the Seattle Seahawks stadium

Concave and Slider for Benicia-Martinez Bridge

http://www.earthquakeprotection.com/benicia_martinez_bridge.html



U.S. Court of Appeals (San Francisco)

http://www.earthquakeprotection.com/product2.html

Passive Energy Dissipation Devices

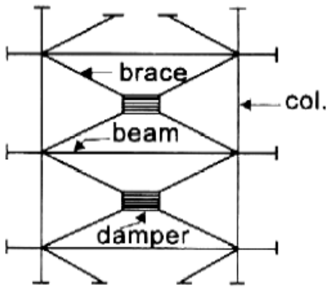
Hysteretic Systems
- *Friction Dampers*
- *Metallic Dampers*

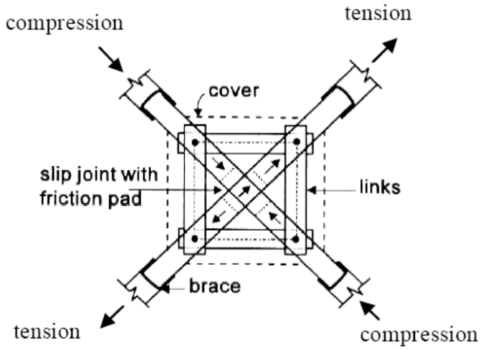
Viscous / Viscoelastic Systems
- *VE Solid*
- *Viscous and VE Fluids*

Tuned-Mass & Tuned-Liquid Dampers

Generally these devices are not used for countering wind loads because of problems associated with residual displacements.

Pall Friction Device





When the brace in tension forces the damper to slip, the damper mechanism forces the other brace to shorten and thus avoid buckling. In this manner, the other brace is immediately ready to slip the damper on reversal of cycle.

http://www.palldynamics.com/main.htm

http://www.tdx.cesca.es/TESIS_UPC/AVAILABLE/TDX-1217103-104653/03Chapt02.pdf

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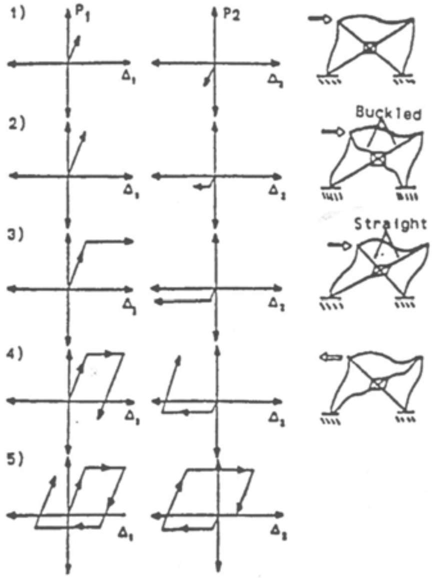
Pall Friction Device - Advantages

- Their performance is independent of velocity and hence exerts constant force for all future earthquakes, design-based earthquake (DBE) or maximum credible earthquake (MCE).
- A much greater quantity of energy can be dissipated in friction than any other method involving the yielding of steel plates, viscous or viscoelastic dampers. Therefore, fewer Pall Friction Dampers are required to provide the required amount of energy dissipation.
- Introduction of high damping results in reduction of forces and deflections.
- Saving in cost of new construction (1-2%) and retrofit of existing buildings (30-60%).

http://www.palldynamics.com/main.htm

Pall Friction Device – Energy Dissipation

1. Early on, both braces are active and behave elastically in tension and compression.
2. Under very small load, the compression brace buckles while the tension brace continues to stretch elastically.
3. The device is set to slip before yielding in the tension brace.
4. When load is reversed, brace 2 can absorb energy in tension.
5. At the completion of the cycle, the resulting areas of the loops are identical for both braces.



Prepared from Dr. Benzoni's SE207 Base Isolation Course Notes

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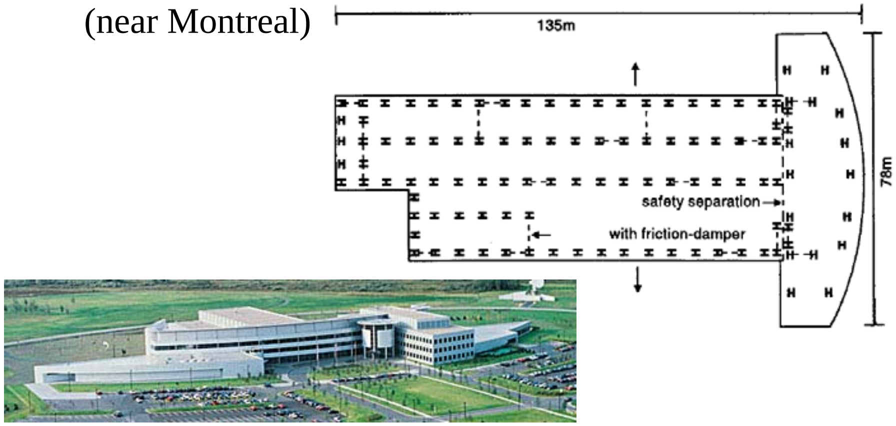
Canadian Space Agency
(near Montreal)

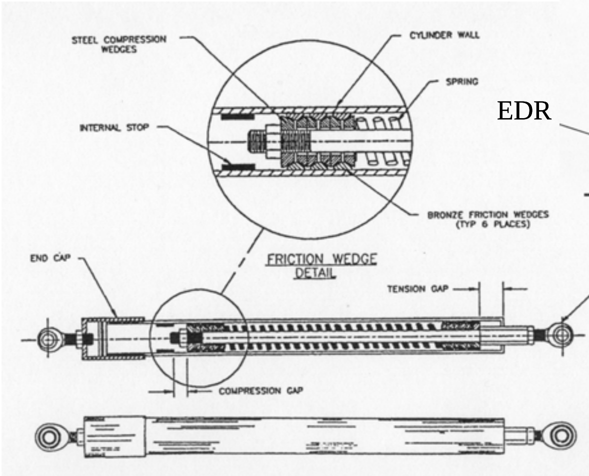


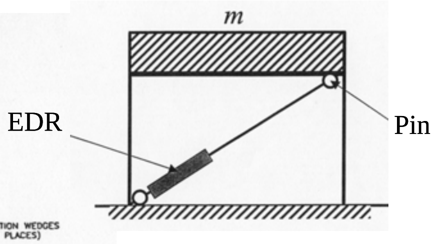
58 friction devices, each with a sliding load of 500 kN, were uniformly distributed throughout the building.

http://www.tdx.cesca.es/TESIS_UPC/AVAILABLE/TDX-1217103-104653/03Chapt02.pdf

Energy Dissipating Restraint (EDR)

(another type of friction device)



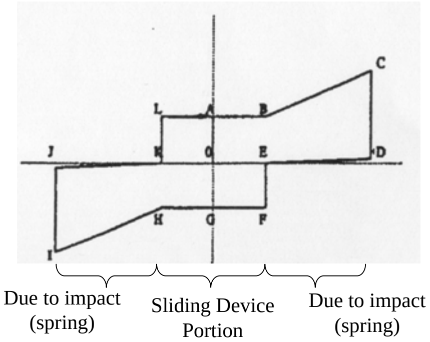


The compression force in the spring, acting on the compression and friction wedges causes a normal force on the cylinder wall. The normal force is proportional to the force in the spring.

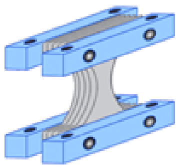
Energy Dissipating Restraint - Continued

The EDR has strong self-centering characteristics and is a friction damper with friction force proportional to the displacement.

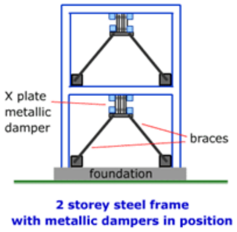
This allows the EDR device to be effective at low and high levels of excitation.

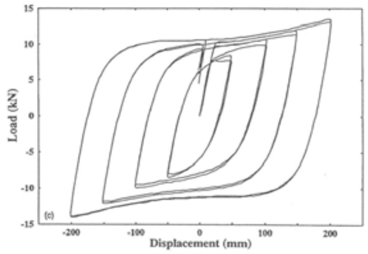


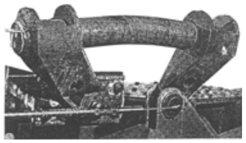
Metallic Dampers



Metallic dampers are cheap devices that dissipate energy through bending. They take advantage of the hysteretic behavior of metals when deformed into the post-elastic range (able to utilize flexural, shear, or axial deformations).

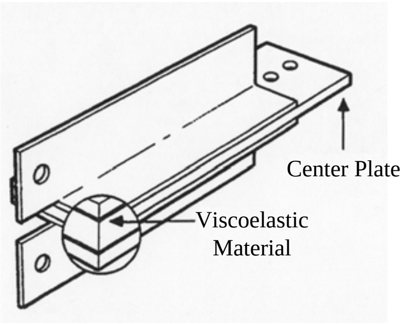






http://www.ideers.bris.ac.uk/resistant/damping_metallic.html

Viscoelastic Solid (VE) Damper



The VE damper is comprised of two layers of an acrylic copolymer (3M) material.

VE dampers have no threshold or activation force level and thus they dissipate energy for all levels of earthquake excitation. This makes them a possible candidate for dissipating wind induced vibration.

Fluid Viscous Devices (FVD)

Fluid Viscous damping reduces stress and deflection because the force from the dampers is completely out of phase with stresses due to flexing of the columns.

This is only true with fluid viscous damping, where damping force varies with stroking velocity.

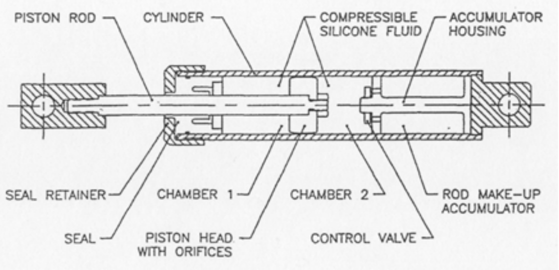
Other types of damping products such as yielding elements, friction devices, plastic hinges, and visco-elastic elastomers do not vary their output with velocity; hence they can, and usually do, increase column stress while reducing deflection.

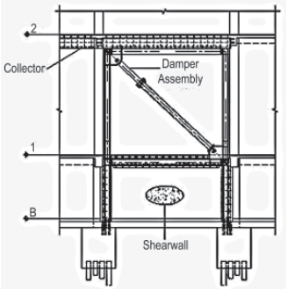
http://www.thomasregister.com/olc/63970008/fvdfaq.htm

Fluid Viscous Devices - Operation

http://www.structuremag.org/archives/2004/july/Structural%20Practices.pdf

Taylor Fluid Viscous Damper





Compressible silicon oil flows through orifices with high velocity, generating heat which is radiated into the surrounding air. This hydrodynamic process dissipates the seismic energy.

FVDs add viscous damping to the structure, and can reduce acceleration and displacement for the most of the frequency range. FVDs are the most useful where engineers desire to reduce displacement without increasing the structure's frequency.

Fluid Viscous Devices - Continued

Linear FVD's may develop excessive damper forces in long period structures subjected to intense ground shaking (develops large structural velocities).

Nonlinear FVD's are attractive in limiting peak damper forces at large velocities while still providing the required supplemental damping.

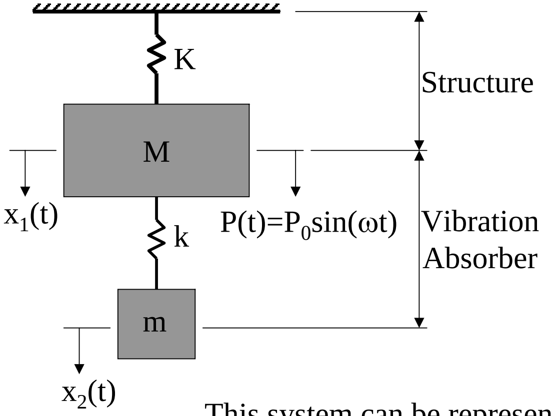
Tuned-Mass and Tuned-Fluid Dampers

Tuned Mass Dampers are mass-spring-dashpot systems that are calibrated to be in resonance with the structure on which they are installed.

They have been proven effective in reducing wind-induced vibrations in high-rise buildings, floor vibrations induced by occupancy activity, and the seismic response of buildings.

TMD's require a relatively large mass and hence a large floor space for their installation. In addition, since they are in resonance with the supporting structure they usually undergo large displacements relative to the structure to which they are connected.

Undamped SDOF System with Tuned-Mass Damper



This system can be represented as a 2DOF system

$$\begin{bmatrix} M & 0 \\ 0 & m \end{bmatrix}\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} k+K & -k \\ -k & k \end{bmatrix}\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} P_0\sin(\omega t) \\ 0 \end{Bmatrix}$$

SDOF System - continued

The forced vibration response is:

$$x_1 = a_1\sin(\omega t) \text{ and } x_2 = a_2\sin(\omega t)$$

where the constants a_1 and a_2 represent the amplitude of the main and secondary mass

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SDOF System - continued

Solving for a_1 and a_2 yields:

$$\frac{a_1}{x_{st}} = \frac{1-\frac{\omega^2}{\omega_a^2}}{\left(1-\frac{\omega^2}{\omega_a^2}\right)\left(1+\frac{k}{K}-\frac{\omega^2}{\Omega_n^2}\right)-\frac{k}{K}} \qquad \frac{a_2}{x_{st}} = \frac{1}{\left(1-\frac{\omega^2}{\omega_a^2}\right)\left(1+\frac{k}{K}-\frac{\omega^2}{\Omega_n^2}\right)-\frac{k}{K}}$$

When the frequency of the absorber (ω_a) is chosen to be equal to the frequency of the disturbing force (ω), the main mass (M) does not vibrate at all ($a_1 = 0$).

For the damper, $a_2 = -\frac{K}{k}x_{st} = -\frac{P_0}{k}$

The force in the damper varies as $-P_0\sin(\omega t)$, which is equal and opposite to the external force.

SDOF System - continued

Consider the case when the damper is in resonance with the main system ($\omega_a = \Omega_n$)

$$\frac{k}{m} = \frac{K}{M} \quad \text{or} \quad \frac{k}{K} = \frac{m}{M} = \mu$$

μ defines the size of the damper as compared to the size of the main system. The amplitudes of the masses become:

$$\frac{x_1}{x_{st}} = \frac{1-\frac{\omega^2}{\omega_a^2}}{\left(1-\frac{\omega^2}{\omega_a^2}\right)\left(1+\mu-\frac{\omega^2}{\omega_a^2}\right)-\mu}\sin\omega t \qquad \frac{x_2}{x_{st}} = \frac{1}{\left(1-\frac{\omega^2}{\omega_a^2}\right)\left(1+\mu-\frac{\omega^2}{\omega_a^2}\right)-\mu}\sin\omega t$$

SDOF System - continued

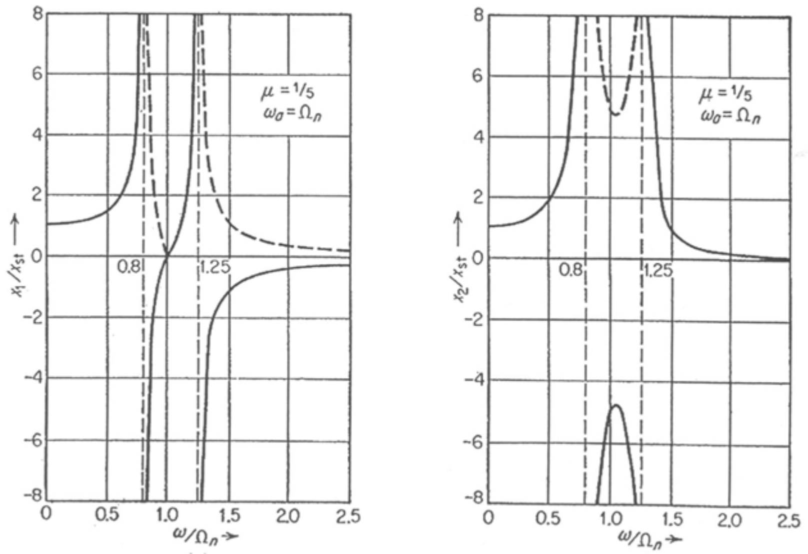
Solving for the two natural frequencies
(by setting the denominators in the previous equations equal to zero)

$$\left(\frac{\omega}{\omega_a}\right)^2 = \left(1+\frac{\mu}{2}\right) \pm \sqrt{\mu + \frac{\mu^2}{4}}$$

For example, when μ = 0.2:

$$\frac{\omega}{\omega_a} = 0.8 \quad \text{and} \quad \frac{\omega}{\omega_a} = 1.25$$

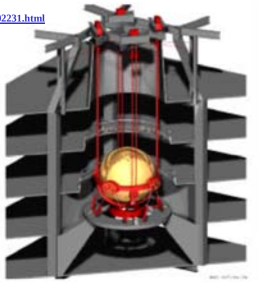
Amplitude spectrum for both masses



Taipei 101

Taipei 101 is a 508 meter tall, 106 floor (101 above ground) skyscraper in Hsinyi District, Taipei, Taiwan.

http://publish.gio.gov.tw/FCJ/past/04102231.html



An 800 ton tuned mass damper is held at the 88th floor, stabilizing the tower against earthquakes, typhoons, and winds. When wind acts on the building, the TMD swings thus absorbing energy and reducing the building's accelerations by 30 to 40%.

http://www.atnet.it/lista/castfc.htm

http://encyclopedia.thefreedictionary.com/Taipei%20101

Citigroup Center

Height to roof: 279 meters

Date built: 1977

Use: Office

Location: New York, United States

The 55 story tower is square-shaped and clad in alternating bands of aluminum and silver glass. The building has a unique sloped top clad in aluminum, originally intended to house apartments. Citigroup Center is elevated 40 meters above the street by four large columns and the central octagonal shaped core. This was to provide light at street level and to avoid a nearby church. The building was one of the first in the United States to have a tuned-mass damper.

http://www.hartmanco.com/about/awards/taipei.htm

London Millennium Bridge

Construction of the bridge began in late 1998. The bridge was completed at a cost of £18.2m and opened on June 10, 2000 (2 months late) but unexpected lateral vibration (resonant structural response) caused the bridge to be closed on June 12 for modifications. The movements were produced by the sheer numbers of pedestrians (90,000 users in the first day, with up to 2,000 on the bridge at any one time). The initial small vibrations encouraging the users to walk in synchronization with the sway, increasing the effect. This swaying motion earned it the nickname the Wobbly Bridge.

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London Millennium Bridge

After extensive analysis, the problem was fixed by the retrofitting of 37 fluid-viscous dampers to control horizontal movement and 52 tuned mass dampers to control vertical movement. This took from May 2001 to January 2002 and cost £5m. After a period of testing the bridge, was successfully re-opened in February 2002.

http://encyclopedia.thefreedictionary.com/London%20Millennium%20Bridge

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