2C09
Design for seismic and climate changes

Lecture 20: Seismic response control

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Lecture outline

20.1 Base isolation.

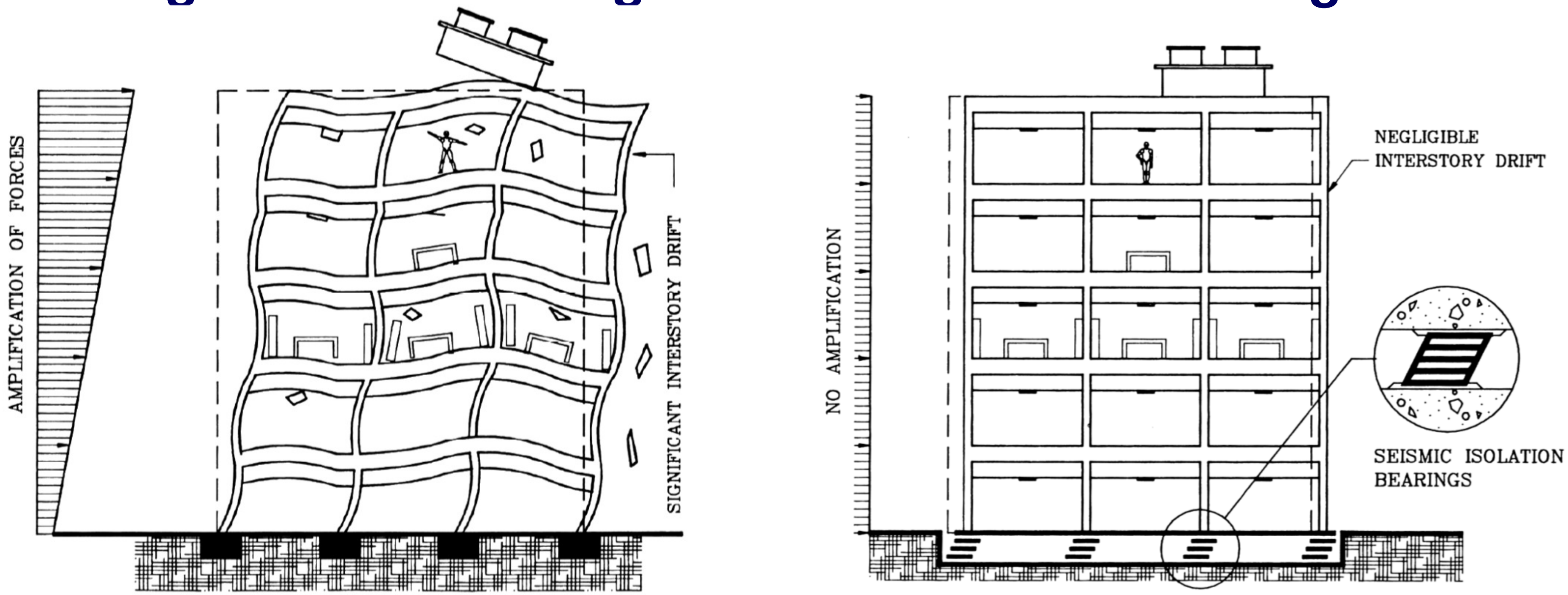
20.2 Passive, semi-active, and active control.

Principles of seismic design

- Traditionally, structures located in seismic zones are designed one of the two approaches:
  - dissipative structural behaviour
  - low-dissipative structural behaviour
- Capacity of the structure to resist seismic action is provided by a combination of strength and ductility:
  - Dissipative structural behaviour: structures with small strength, relying on ductility to resist the seismic action. Exploiting the ductility of the structural system implies acceptance of large plastic deformations, which means damage to both structural and non-structural components.
  - Low-dissipative structural behaviour: structures relying on strength, with reduced ductility. Large strength implies large stiffness, which results in large accelerations and consequently damage to equipment.

Concept of base isolation

- **Seismic action consist in ground displacement applied to the supports of the structure. As a results, the structure experiences deformations and accelerations, often larger than the one of the ground. Base isolation consists in decoupling the structure vibration form the ground vibration, preventing most of the horizontal movement of the ground from being transmitted to the buildings.**

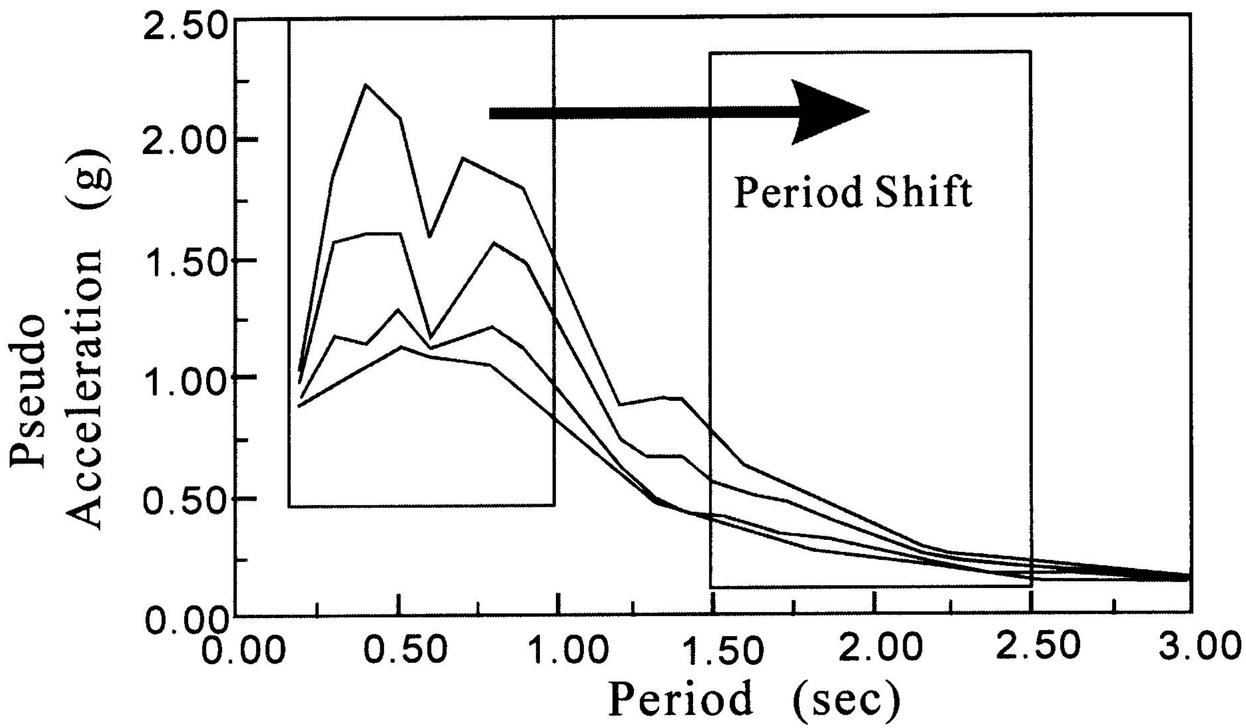


Base isolation: implementation

- Seismic isolation is implemented by inserting between the foundation and structure of devices with:
  - small lateral stiffness;
  - large vertical stiffness;
  - large damping.
- A device fulfilling the requirements above has the following effects:
  - reduced lateral stiffness of the structure (increases period)
  - increases the damping.
- Vertical stiffness of isolation devices should be comparable with the one of structural members (e.g. columns), in order to assure an adequate behaviour under gravity loading.
- The isolation devices should not be too flexible, in order to prevent discomfort of building occupants under wind-induced vibrations.

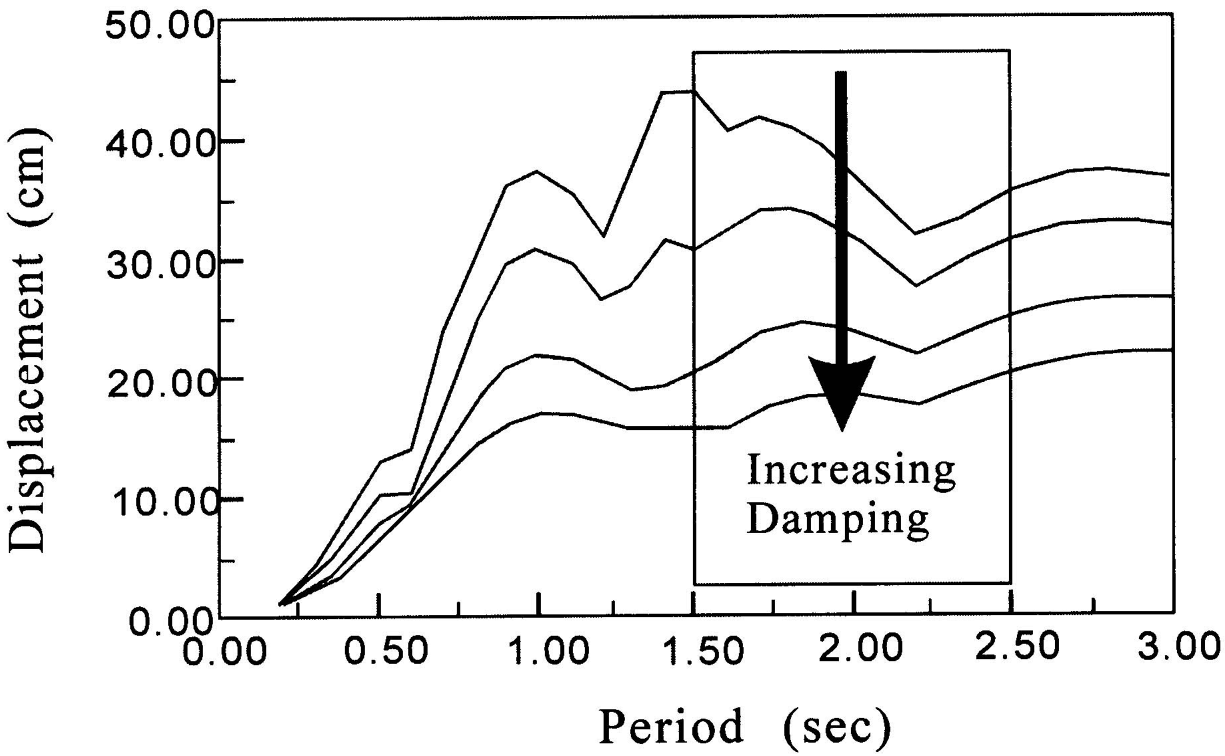
Base isolation: period lengthening

- **A base-isolated structure has a substantially-larger period of vibration than a structure with fixed base.**
- **The effect of period lengthening:**
  - **reduction of spectral accelerations (and related forces)**
  - **increase of spectral displacements**



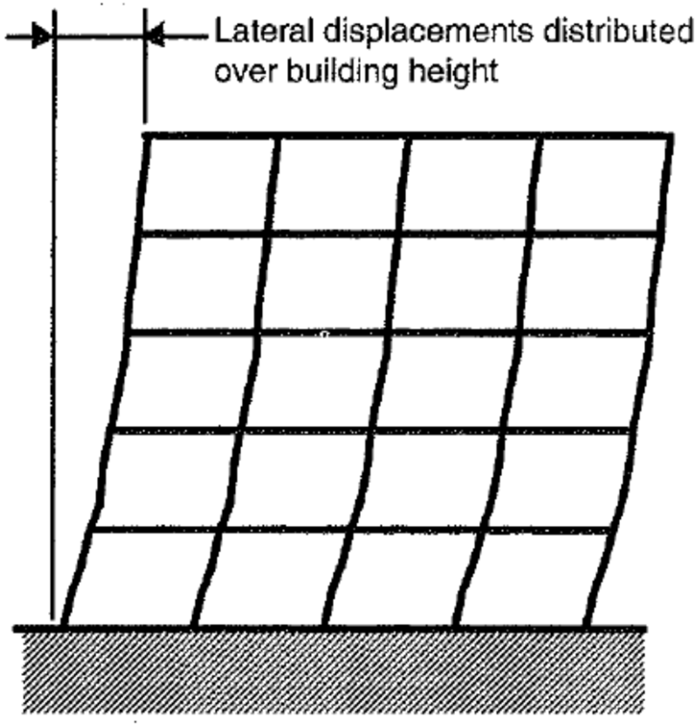
Base isolation: increase of damping

- As a result of period increase, the structure – isolator assembly will experience larger displacements.
- To reduce this effect, it is preferable that the isolating device offer a significant damping, which reduces displacements.

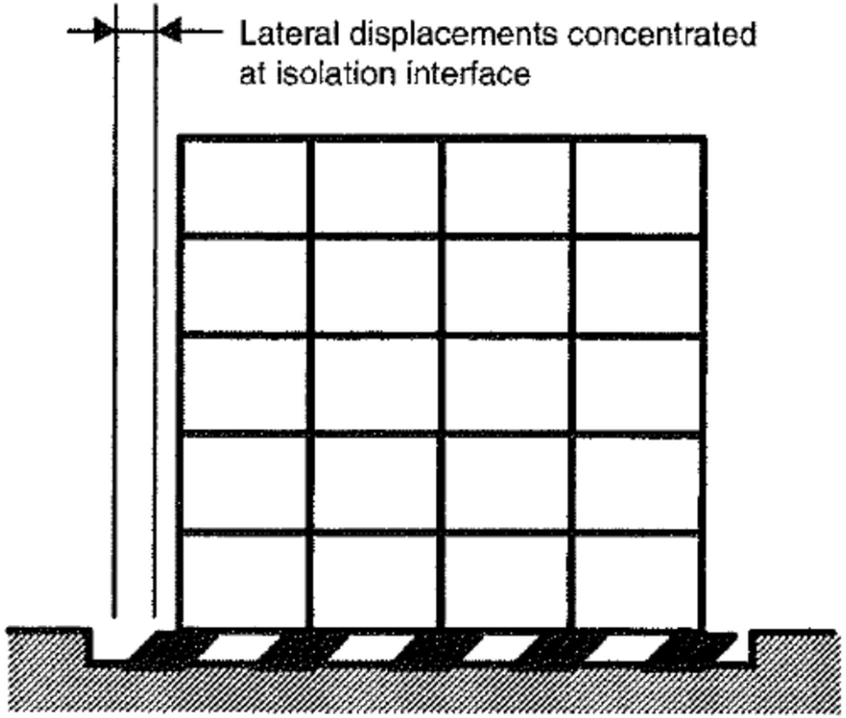


Base isolation: effects

- **In a structure with fixed base lateral deformations are distributed along the building height (a MDOF system).**
- **In a base-isolated structure lateral deformations are concentrated in the isolation devices, the structure behaving essentially as a SDOF system.**



(a) Fixed base building



(b) Seismically isolated building

Base isolation: effects

Base isolation: efficiency

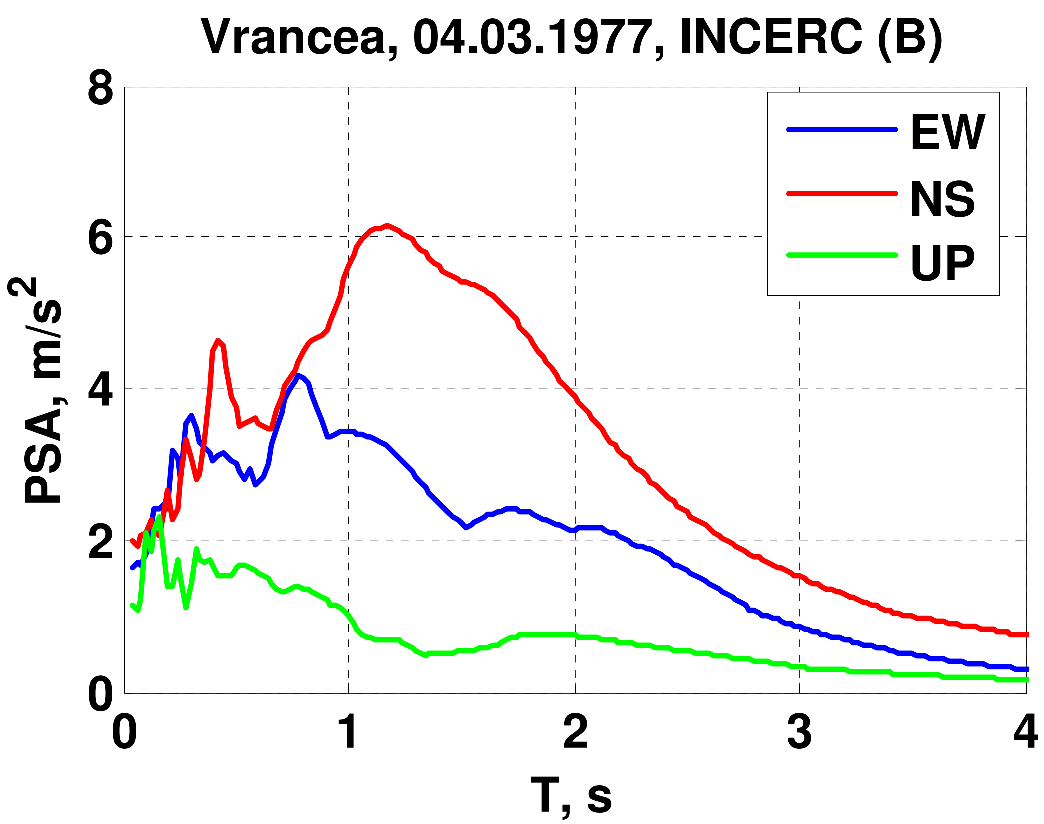
- Base isolation is efficient for rigid structures (low-rise and medium-rise buildings), with periods of vibration below ≈1 sec. Using isolator devices, the period can be increased to 1.5-2.5 seconds, getting an important reduction of seismic forces induced in the structure. High-rise buildings have large period of vibration, their design being often governed by wind loading.
- Base isolation is efficient for structures with a low ratio between the height and dimension in plan of the building. Overturning leads to difficulties in operation and design of isolators in high-rise structures.

Base isolation: efficiency

- **Base isolation is important for the horizontal component of the seismic action. When the vertical component of the seismic action is important (structures located close to the seismic source), base isolation is not a good option.**
- **Base isolation is efficient for ground motions with a high frequency content in the short-period range (small values of control period T_C – stiff soils). In case of ground motions with high frequency content in the long-period range (large values of control period T_C – soft soils), increase in period can lead to larger seismic forces and larger deformation demands. Base isolation is not efficient in this case.**

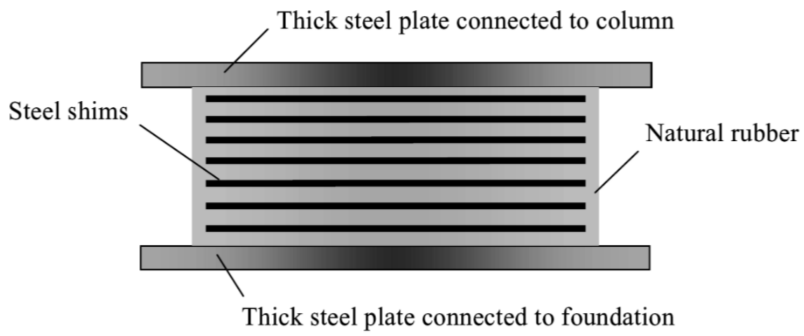
Base isolation: efficiency

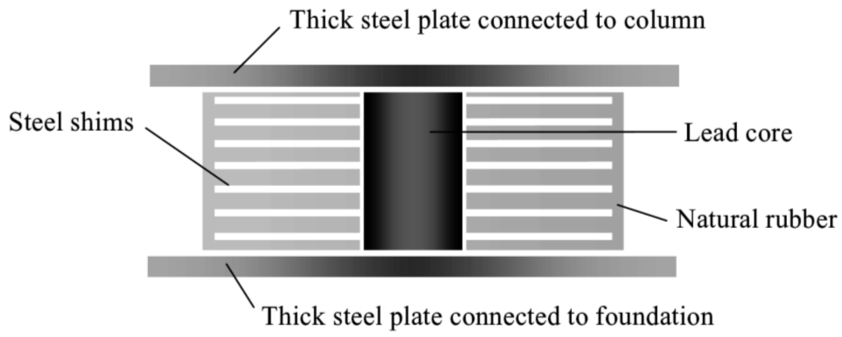
- **Examples of seismic motions with high frequency content in the long-period range:**
  - **Vrancea seismic source and weak soil conditions in Bucharest**
  - **Basin effect and weak soil conditions in Mexico-City.**

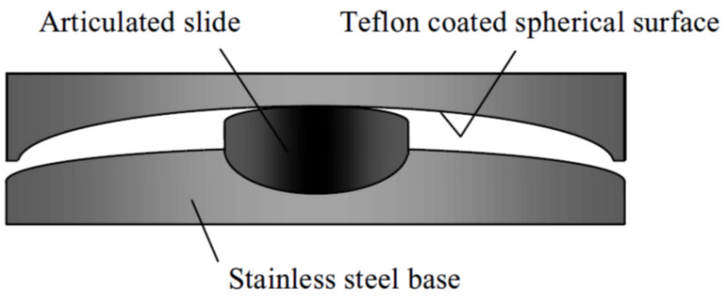


Base isolation: devices

- **There are different types of bearings (isolators). Most common ones can be classified in two categories:**
  - **elastomeric bearings**
  - **sliding bearings**

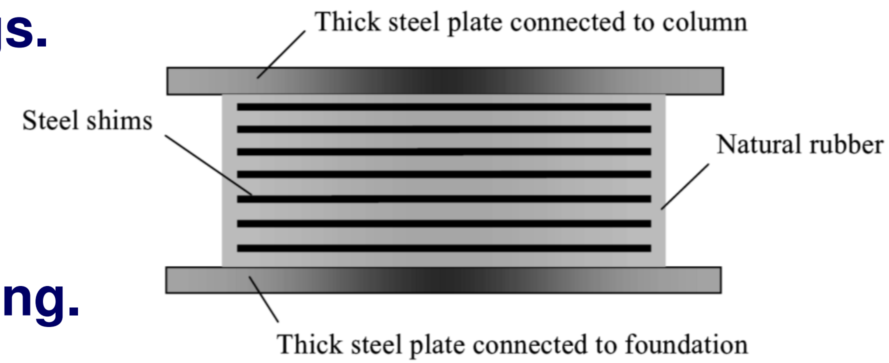






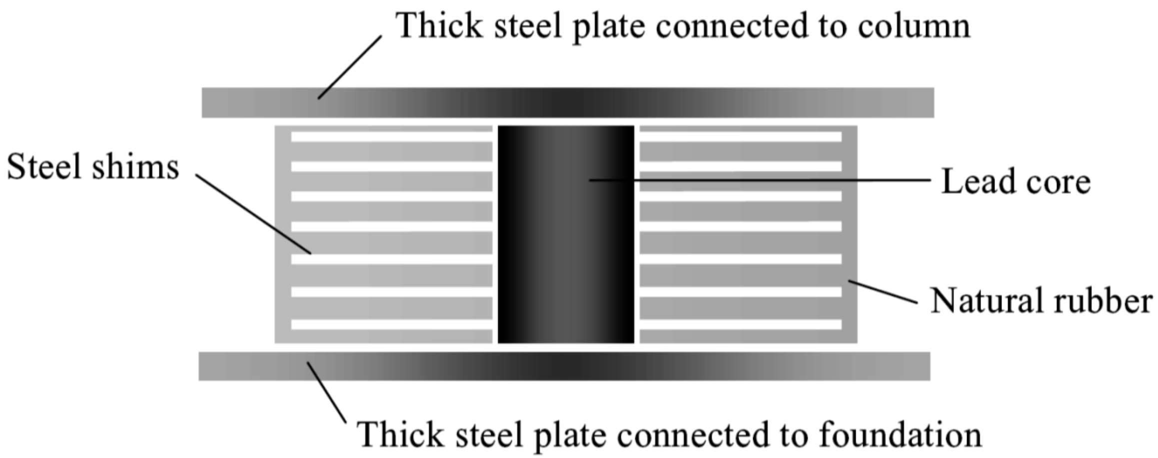
Base isolation: devices

- Elastomeric bearings were originally made from natural rubber; later on, synthetic rubbers, such as neoprene, were introduced.
- Properties of elastomeric bearings can be improved by adding steel plates or shims
  - keeps the rubber layers from laterally bulging and
  - reduces the bearing's vertical deformation (large vertical stiffness).
- Due to low critical damping (2%-3%), elastomeric bearings have little resistance to service load, and additional damping devices are required in order to control higher lateral displacement.
- Are easily manufactured, and the manufacturing cost is relatively low compared to other types of bearings.
- Their mechanical properties are independent of temperature and aging. Are very stable and do not exhibit creep under long-term loading.



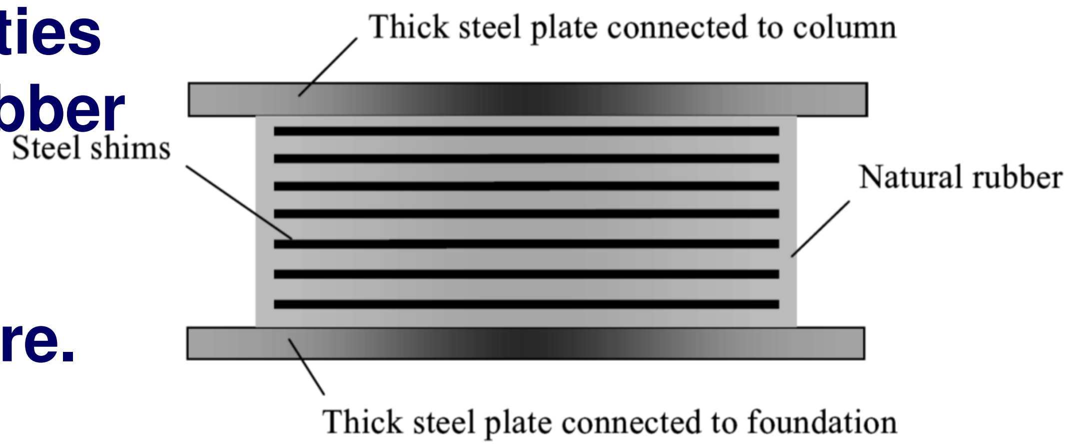
Base isolation: devices

- <u>Lead-Plug Bearings</u> are fabricated by plugging a lead core into the elastomeric bearing.
- The performance of the lead-plug bearing depends on the imposed lateral force.
  - If the lateral force is small, the movement of the steel shims is restrained by the lead core, and the bearing displays higher lateral stiffness.
  - As the lateral force becomes larger, the steel shims force the lead core to deform or yield, and the hysteretic damping is developed with energy absorbed by the lead core.
- The equivalent damping of the lead-plug bearing varies from 15% to 35%.



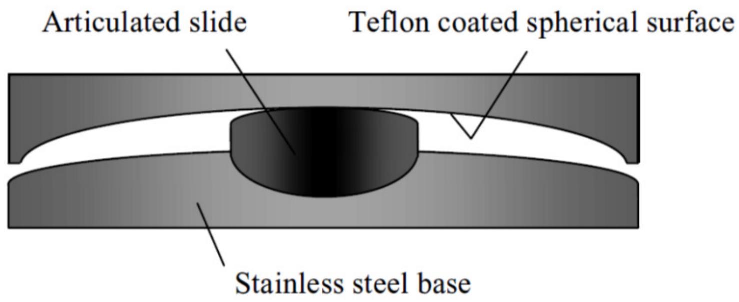
Base isolation: devices

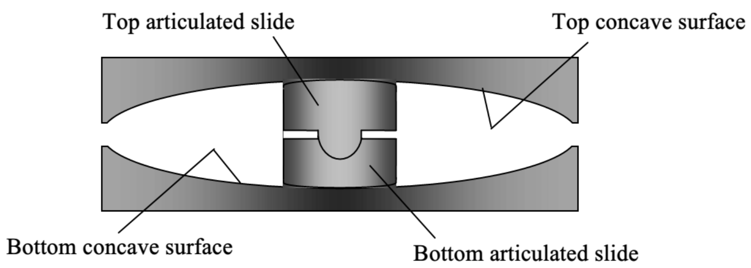
- High-damping rubber bearing. An effective method to increase the damping of the electrometric bearing is to modify the rubber compounds no matter whether the rubber is natural or synthetic.
- For example, adding carbon black or other types of fillers to the natural rubber changes the rubber's properties and results in higher damping.
- For natural rubber, the effective damping changes from approximately 15% at low-shear strain to 10% at high-shear strain.
- The mechanical properties of the high-damping rubber bearing are affected by the effects of aging and temperature.



Base isolation: devices

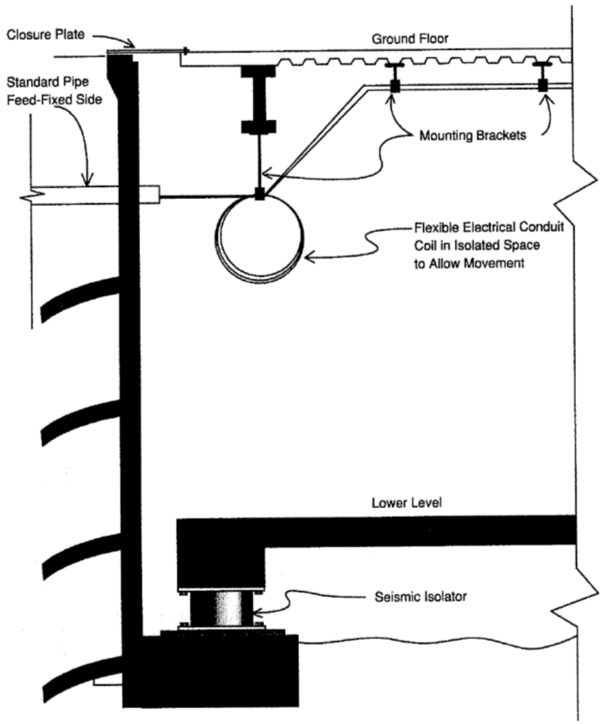
- Friction pendulum bearings are realised from components with low friction in direct contact. If plane surfaces are used alone, the building is unable to return to its original position after an earthquake.
- To reduce the distance to the center of the bearing after an earthquake, a friction bearing with a spherical or concave sliding surface was developed.
  - The spherical sliding surface is normally coated by Teflon with approximately 3% friction coefficient.
  - The imposed lateral force pushes the bearing in both horizontal and vertical directions.
  - A component of applied vertical load along the tangential direction to the spherical surface helps the bearing move back to the center.

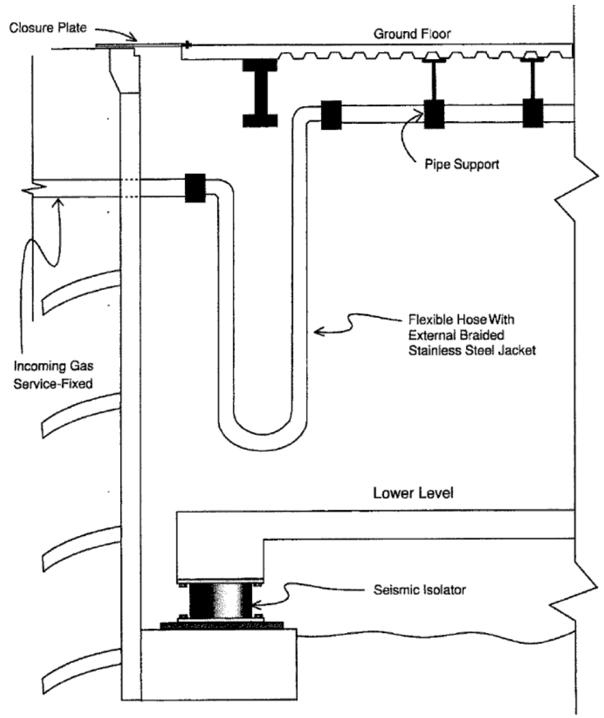




Base isolation: seismic gap

- Lateral deformations in a base-isolated structure are concentrated at the base of the building.
- A seismic gap must be provided to accommodate the free movement of the structure with respect to the ground.
- Flexible connections must be provided for utility lines crossing the seismic gap.





Structural control

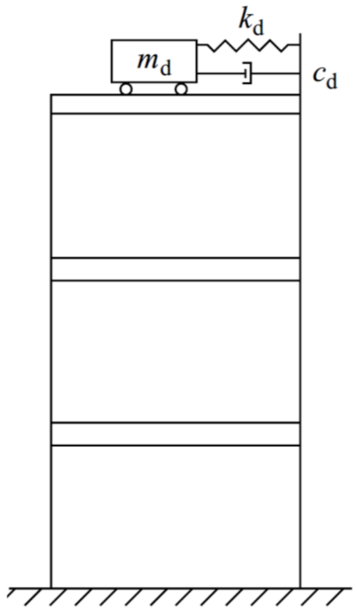
- Structural control is basically the modification of the properties of a structure, in order to achieve a structurally desirable response to a given external load.
- The modification of the structure's properties includes changes in the damping and stiffness of the structure, so that it can respond more favorably to the external loading.
- Structural control is most typically employed in cases involving dynamic loads, so that the potential exists for modification of the structure's properties to permit a reduction in the level of excitation transmitted to the structure.
- Systems for control of structural response can be divided into three groups: passive, active, and semi-active.

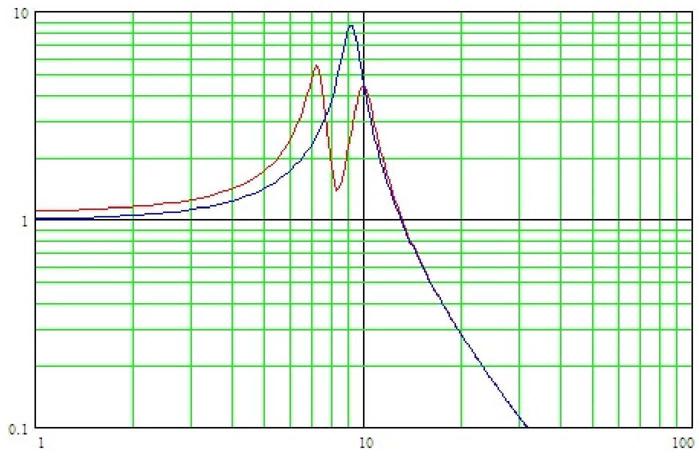
Passive control

- Passive energy-dissipating systems use mechanical devices to dissipate a portion of structural input energy, thus reducing structural response and possible structural damage.
- Typical passive systems are
  - tuned mass dampers (TMDs),
  - tuned liquid dampers (TLDs),
  - friction devices,
  - metallic yield devices,
  - viscous-elastic dampers, and
  - viscous fluid dampers.

Passive control

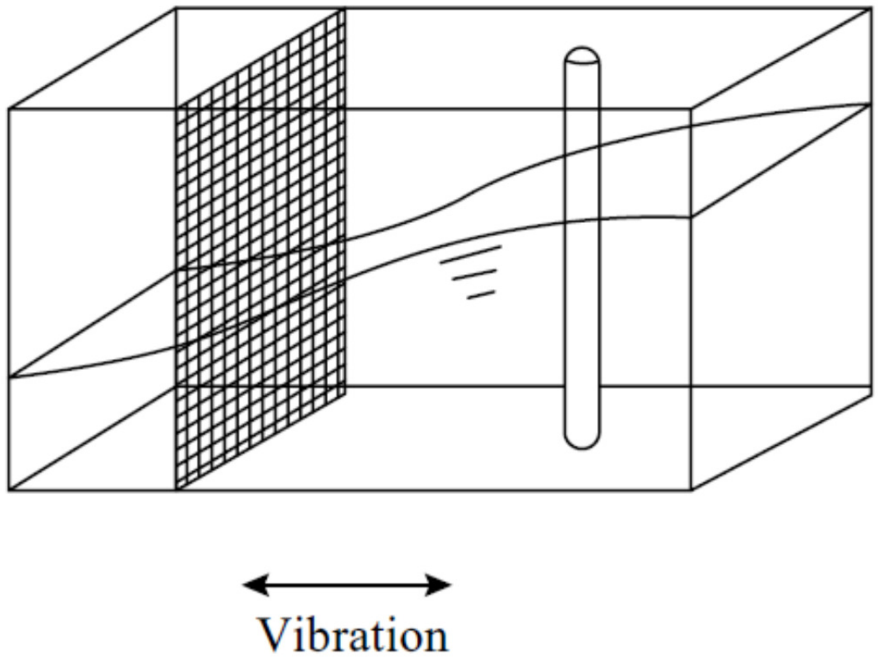
- <u>Tuned mass dampers</u>, in their simplest form, consist of an auxiliary mass (m_d)-spring (k_d)-dashpot (c_d) system anchored or attached to the main structure, usually on the top of the structure
- The TMD responds to structural vibrations, and part of the energy transfers to the vibration energy of the TMD. The TMD damping dissipates its vibration energy, and as a result, the vibration energy of the structure is absorbed by TMD damping.





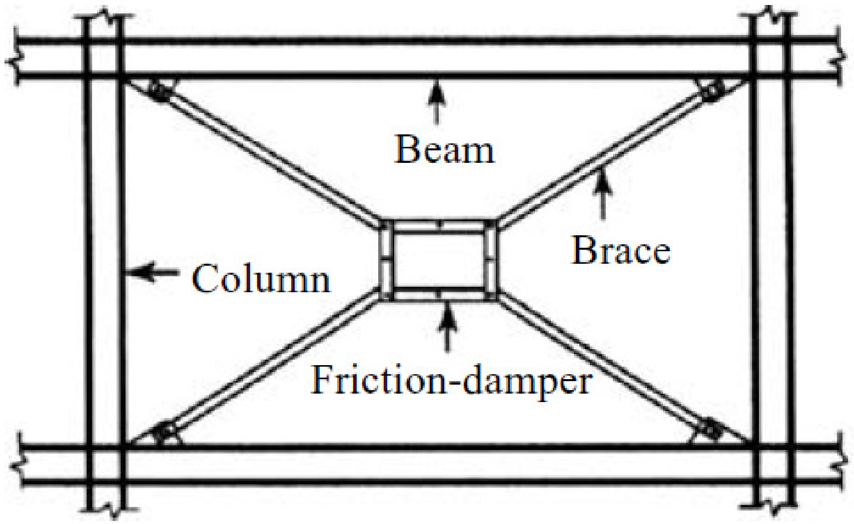
Passive control

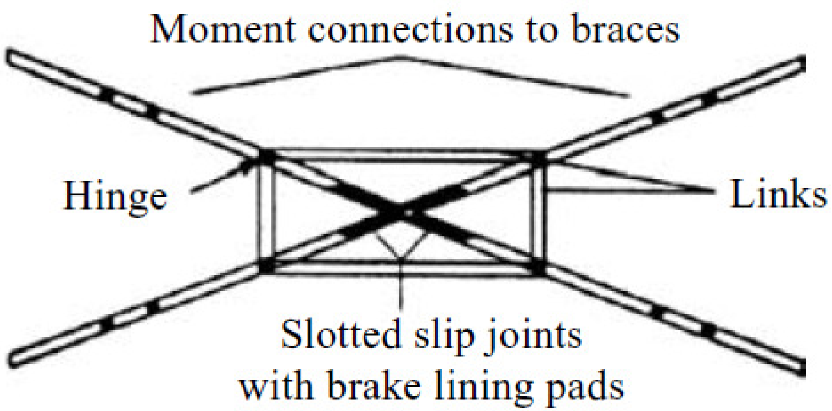
- In <u>tuned liquid dampers</u> (TLDs) water or some other liquid serves as the mass in motion, and the restoring force is generated by gravity.
- The structural vibration shakes the TLD and induces the liquid movement inside the container.
- The turbulence of the liquid flow and the friction between the liquid flow and the container convert the dynamic energy of the fluid flow to heat, thus absorbing structural vibration energy.



Passive control

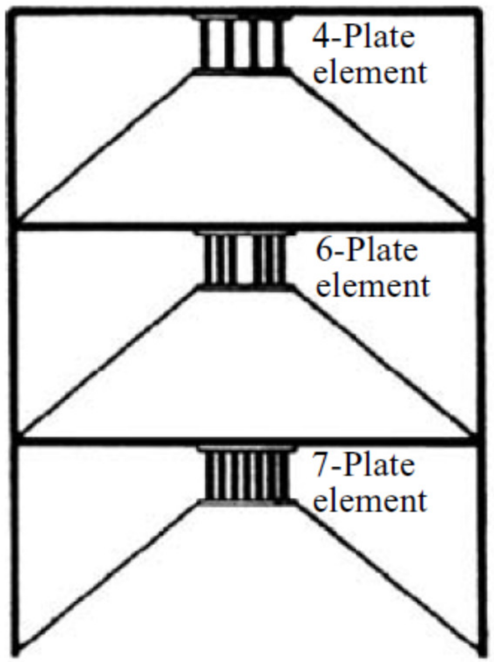
- **Friction is an effective, reliable, economical, and widely applied mechanism to dissipate kinetic energy by converting it to heat. To achieve this essential friction, the friction damper must have two solid bodies that slide relative to each other.**
- **Simple to construct and effective for seismic protection.**
- **Difficult to maintain their mechanical properties over prolonged time intervals (corrosion, temperature changes, and relaxation of the sliding metal interface).**

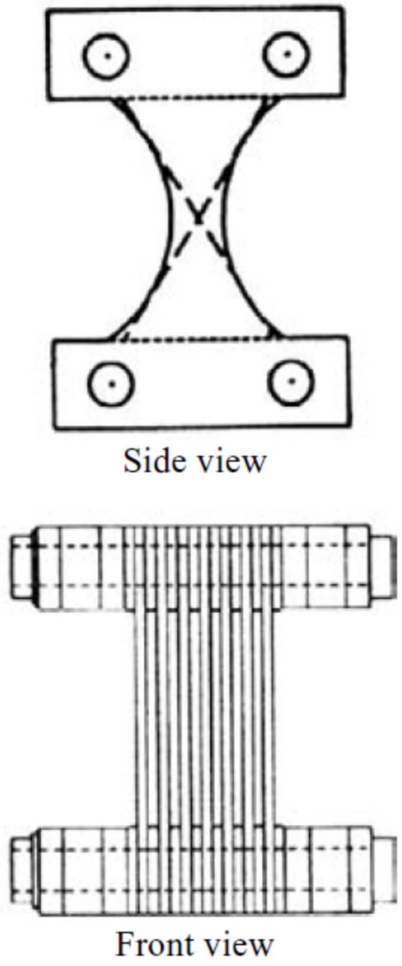




Passive control

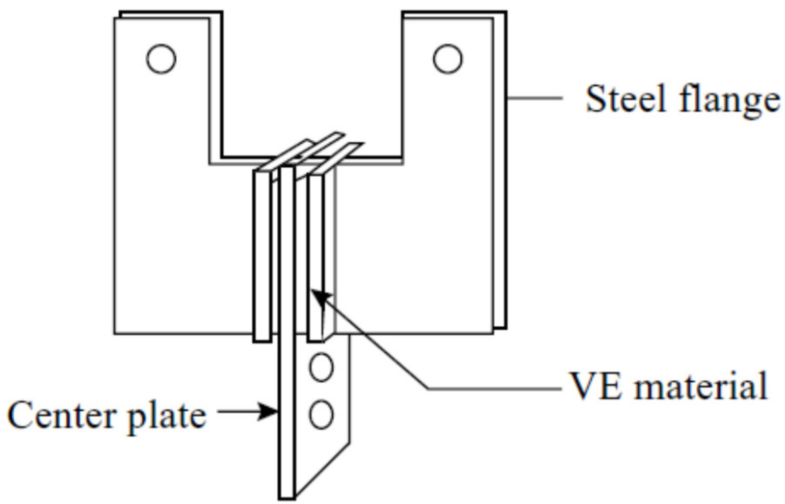
- The traditional seismic-resistant design of structures depends on postyield ductility of structural members to dissipate earthquake input energy.
- This concept led to the idea of installing separate <u>metallic hysteretic devices</u> in a structure to absorb seismic energy.

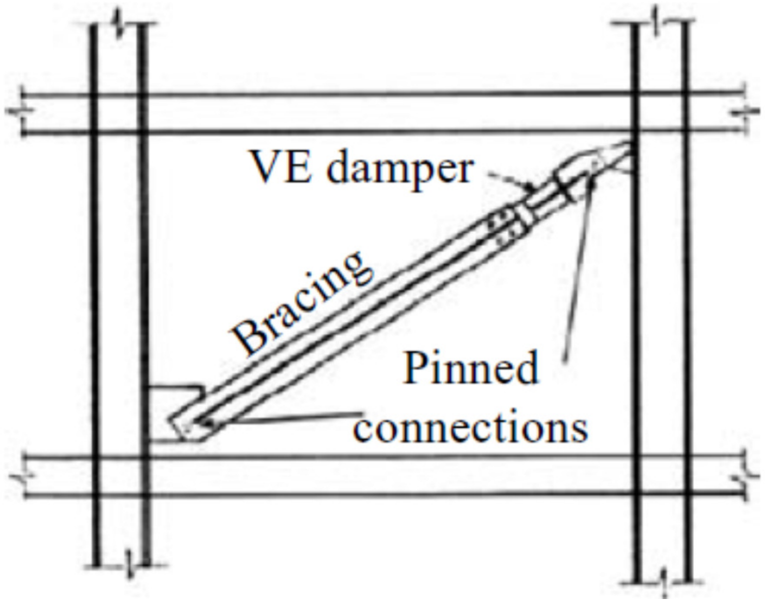




Passive control

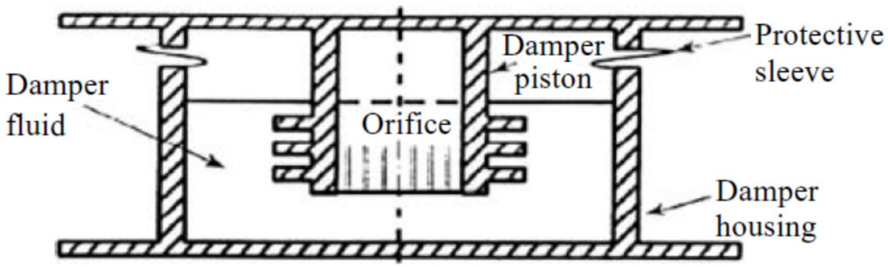
- <u>Viscoelastic (VE) dampers</u> utilize high damping from VE materials to dissipate energy through shear deformation. Such materials include rubber, polymers, and glassy substances. A typical VE damper consists of VE layers bonded to steel plates.
  - VE dampers generally behave linearly, which simplifies the analysis and design process.
  - However, VE dampers have the disadvantage of being frequency and temperature dependent

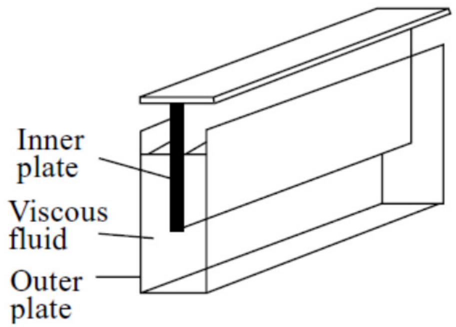




Passive control

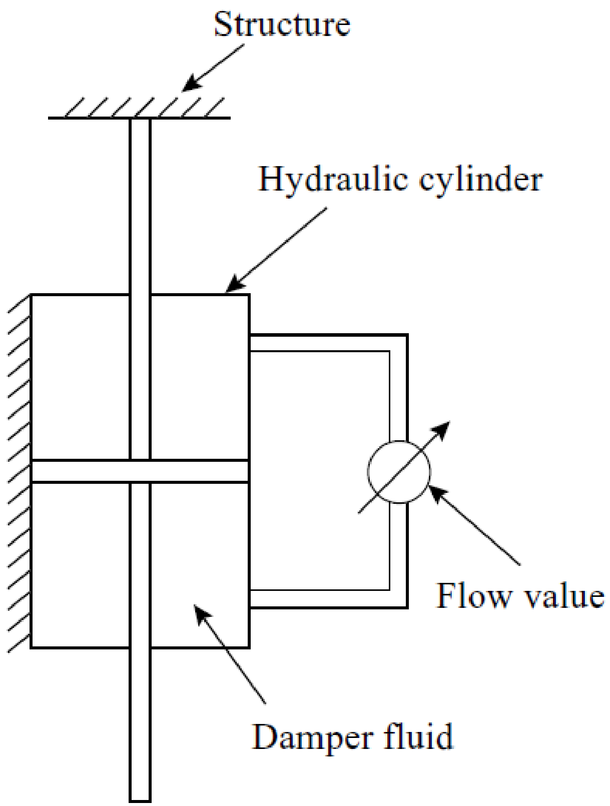
- A classic implementation of viscous fluid damper is achieved with classical dashpot, and dissipation occurs by converting kinetic energy to heat as a piston moves and deforms a thick, highly viscous fluid.
- The relative movement of damper piston to damper housing drives the viscous damper fluid back and forth through the orifice. Energy is dissipated by the friction between the fluid and the orifice.





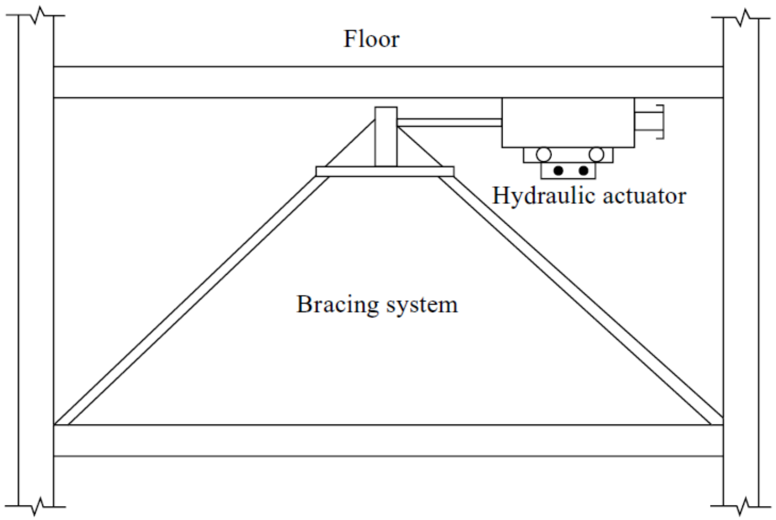
Semi-active control

- Systems using semi-active dampers are adaptive system that gather information about the excitation and structural response and then adjusts the damper behavior on the basis of this information to enhance its performance.
- A semi-active damper system consists of sensors, a control computer, a control actuator, and a passive damping device.
- The sensors measure the excitation and/or structural response. The control computer processes the measurement and generates a control signal for the actuator. Then the actuator acts to adjust the behavior of the passive device.



Active control

- Active seismic response control special devices, such as electrohydraulic actuators, to generate the required control force against earthquake loading by feeding back the measured structural response.
- This control force can serve as extra damping, thus reducing structural vibration under traffic, wind, and earthquake excitations.
- Smart structures using active control systems employ external power to generate the control force, which is directly applied to the structure to reduce its response. Huge force-generating equipment and large external power supplies are required for active seismic response control.



References / additional reading

- Franklin Y. Cheng, Hongping Jiang, Kangyu Lou, 2008. "Smart Structures: Innovative Systems for Seismic Response Control". CRC Press.
- Ronald L Mayes and Farzad Naeim, 2003, "Design of Structures with Seismic Isolation", Chapter 14 in "The seismic design handbook"

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