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SEISMIC ISOLATING SYSTEMS
CLASSIFICATION, PROPERTIES AND UTILIZATION

BY

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Abstract. Flexible buildings can produce excessive vibration due to wind action, thus affecting the comfort of residents but also the structural system. To ensure the functional performance of the flexible structure have been adopted several solutions (flexible structures driven by wind and earthquake require dampers) while those driven only by the earthquake are rigid and require base isolation systems. An overview of measures to reduce structural response including a discussion of auxiliary damping devices, as well as recent examples of their use in countries such as USA, Japan, Turkey, Italy, is presented.

Key words: passive isolation systems; dampers; earthquake.

1. Introduction

The main objective of seismic isolation is to protect structures from destructive actions. Therefore we need to know very well the components of an earthquake to can counteract their damaging effects. This components were determined by researchers after long periods of observation, such as the existence of a peak acceleration of ground movement, a large vertical displacement and a long period of seismic waves which can be very destructive,

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this is way the seismic base isolation system can be very vulnerable at earthquakes of long vibration periods, (Lu *et al.*, 2003).

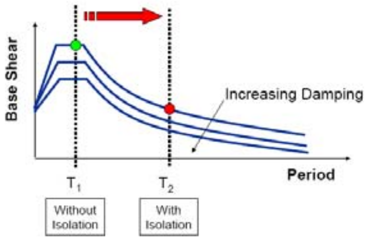


Fig. 1 – Increasing period of vibration of an isolated and unisolated structure (Symens, 2009).

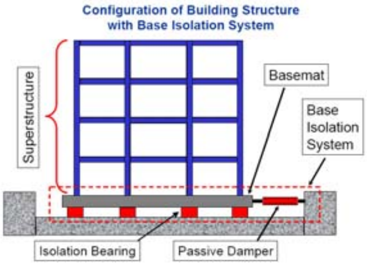


Fig. 2 – Base isolated structure (Symens, 2009).

Base isolation systems attenuates the effect of damage due to earthquake by reducing acceleration and interstory drifts, also increasing the period of vibration of the structure, and thereby avoiding structural damage not only for structural but also for unstructural elements (Fig. 1), being one of the most used and widely accepted seismic isolation systems (Ramallo *et al.*, 2002).

2. State Clasification

2.1. United States of America

a) In America one of the most used methods is the base isolation of structures with passive isolation systems (Fig. 4). An example of this type of isolators are *friction pendulum system* used for the isolation of Pasadena City Hall building in California (Fig. 3). During the seismic rehabilitation the original basement was removed, and were installed 240 pendulum friction between the new foundation and new basement, made of upper and lower concave plates and an inner sliding system. This was mainly due to reduced cost of this project, simple assembly can be executed faster (Earthquake Prot. Syst.).

Fig. 3 – Pasadena City Hall, California.

Fig. 4 – Friction pendulum system.

b) Another base isolation with passive system used in the U.S. are elastomeric bearings: *lead rubber bearings* (Fig. 6). A good example in this case is USC University Hospital building in LA (Fig. 5), isolated with this type of isolators in 1991.

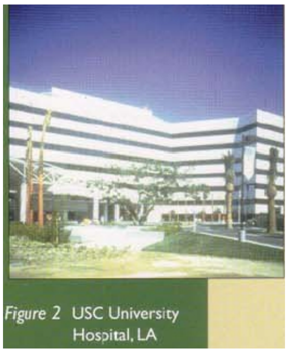


Fig. 5 – USC University Hospital, L.A.

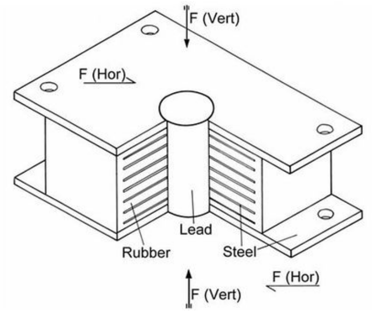


Fig. 6 – Elastomeric bearing.

c) Buildings isolated with *passive mass dampers* and *tuned liquid dampers*. One of the most recent applications of this isolation system was in 1977 in Boston in Hancock Tower building (Fig. 7) at floor 58 where two devices of mass damper were installed at opposite ends.

Fig. 7 – Hancock Tower Hill Boston.

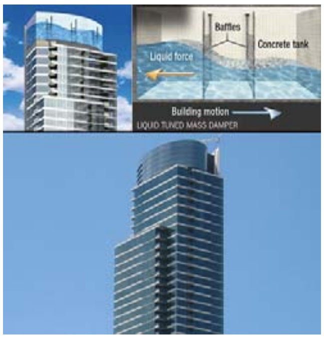


Fig. 8 – One Rincon San Francisco.

The system consists of a lead box of dimensions 5.2 × 5.2 × 1 m and weighs 300 t. Lead box is attached to the building with shock absorbers. A building that uses liquid damper control device is One Rincon Hill in San Francisco (Fig. 8) (Kareem *et al*., 2003).

Buildings insulated with passive systems: *viscoelastic dampers*. These systems typically use as material, rubber which can deform under shear force, offering both strength and energy dissipation.

In U.S. there are few insulated buildings with this type of isolation. For exemple World Trade Center building (Fig. 9) which was the first insulated building, and SeaFirst Columbia Building in Seattle (Fig. 10) (Kareem *et al*., 2003).

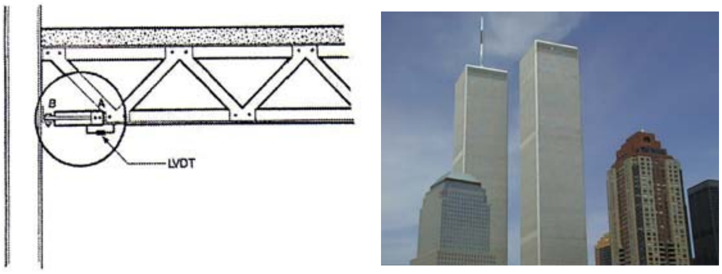


Fig. 9 – World Trade Center.

Fig. 10 – SeaFirst Building.

2.2. Japan

In Japan seismic design has always a priority, being developed several mechanisms of buildings protection.

a) An example of the insulators we meet are the elastomeric bearings: *lead rubber bearings*.

High-City Kiyosumi Sirakawa Station Plaza, 1997

Fig. 11 – High-City Kiyosumi Sirakawa Station Plaza.

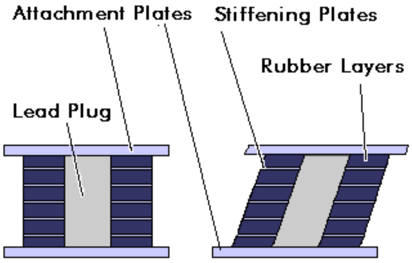


Fig. 12 – Lead rubber Bearing.

One of the residential buildings insulated with lead rubber bearings (Fig. 12) is High-City Kiyosumi Sirakawa Station Plaza (Fig. 11), built in 1997, were the insulators have the dimensions of 12 × 1.5 m diameter.

b) Another type of insulators are *viscoelastic dampers* (Fig 14). In Japan are used with the view to reduce the displacements of the structures caused by wind. An exemple of this building is Riverside Torishima, Symbol Tower Hill (Fig. 13); 8 insulators are installed on every level from level 1 to 19 and four insulating level between levels 20...38 (Kareem *et al.*, 2003).

Fig. 13 – Torishima Riverside Hill, Symbol Tower.

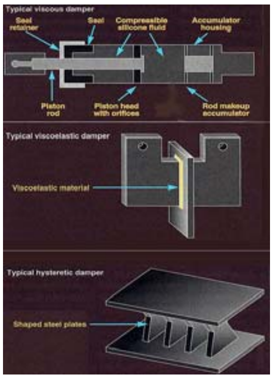


Fig. 14 – Viscouselastic dampers.

c) Building insulated with passive system – *tuned mass dampers*. A building of this type we meet in Osaka, Crystal Tower (Fig. 15). A pendulum

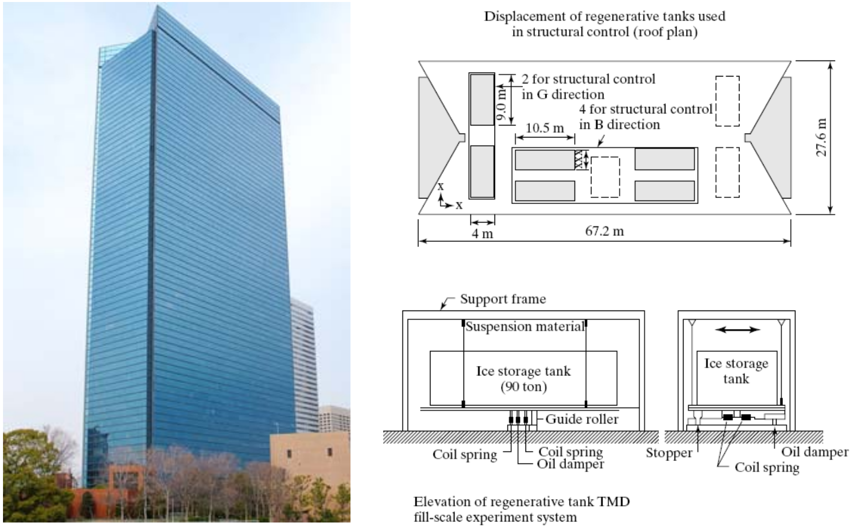


Fig. 15 – Crystal Tower.

mass was introduced to decrease the damping of wind-induced motion by approximately 50%. Six of the nine tanks of ice are hanging from the top of the roof beams and used as a pendulum mass. Another example is the Tokyo Sky Tree (Fig. 16) to be completed in October 2011 (Kareem *et al*., 2003).

Fig. 16 – Tokyo Sky Tree.

d) Buildings insulated with passive systems – *tuned liquid dampers*. An application in this regard was made on the level 158 of the building Gold Tower (Fig. 17), Japan where are installed 10t of liquid dampers in 16 units, wich has reduced the structural response between half and one third of the original response (Kareem *et al*., 2003).

Fig. 17 – Gold Tower.

c) An other type of seismic insulation systems uses *active dampers*. The first installation of such a system was developed by Kajima Corporation in 1989, which has equipped the Siewa Building, Kyobashi building (Fig. 18).

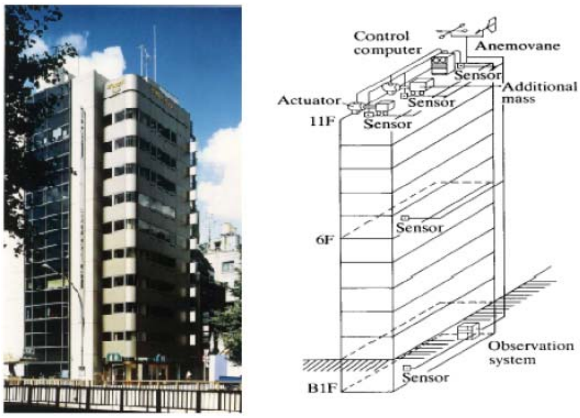


Fig. 18 – Kyobashi Siewa Building (Agarofinei, 2010).

Fig. 19 – Herbis Building.

The system was installed to protect the building from wind and earthquakes and is able to respond to vibrations in 0.01 s, because of sensors that detect motion. This device is installed at the basement of the building and especially at levels 6 and 11. Two active mass dampers were installed, a large one of 4 t in the middle of building to control large oscillations, and the another one little of 1 t installed at the edge of the building to counteract the torsion. A more recent application of this system is a building in Osaka, Herbis Building (Fig. 19), 1997 (Kareem *et al.*, 2003).

2.3. Italy

One of the earliest uses of seismic insulation systems in this country is the *friction pendulum system* (Fig. 20). Following the 2009 earthquake the

Aquila neighborhood have been rebuilt using this type of insulation. Friction surface is covered with a non-corrosive material (Teflon); the curvature of the friction damping is 4 m, obtaining 20% with a displacement of 260 mm (Consenza & Manfredi, 2010).

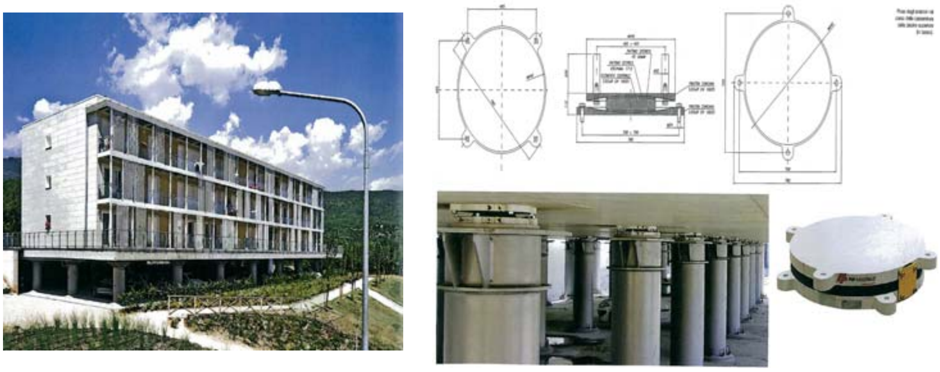


Fig. 20 – Aquila neighborhood buildings and friction pendulum system used (Consenza & Manfredi, 2010).

2.4. Turkey

After the severe earthquake in 1999 engineers have started to be more concerned about this problem. Thus appeared the first buildings equipped with seismic systems. For example the building of Erzurum State Hospital in eastern Turkey (Fig. 21) became one of the largest hospitals in the world with base insulation systems.

Fig. 21 – Erzurum State Hospital (Ihsan, 2008).

Fig. 22 – RC International Building of the Antalya Airport (Ihsan, 2008).

Engineers have been concerned about two things: to suppress the shear force at base at $0.1G$ (G = building weight), and the displacement of insulators to be not less than 600 mm during the maximum considered earthquake. This building was insulated with five types of lead rubber bearing with diameters between 800...110 mm . Another building insulated with lead rubber bearings is RC Building of the Antalya International Airport (Fig. 22 – Ihsan, 2008).

3. Common and Particularities Properties of Seismic Insulators

Base insulation systems are installed between the foundation and structure to protect it from damages during the earthquake. Insulators reduce lateral forces and movements wich are transmitted into the structure.

3.1. Elastomeric Bearings

Usually this type of insulators provide 2...3% of critical damping (Fig. 23). One way to increase the damping is to use high-damping insulator containing natural rubber, oil or resin or other fillers that can grow up to 20% degree of damping.

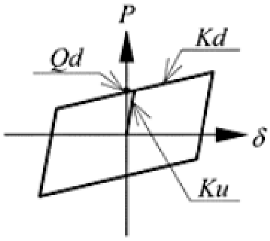


Fig. 23 – Bilinear histeretic model (Symans, 2009).

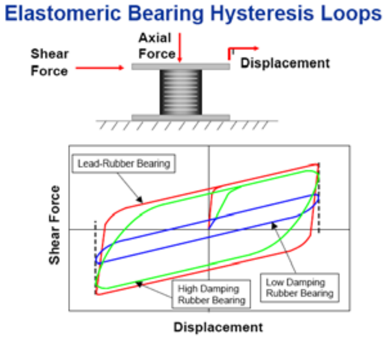


Fig. 24 – Hysteretic diagram of different types of elastomeric bearings (Symans, 2009).

Another option is to install inside of a small damping rubber bearing a lead core to increase energy dissipation by hysteretic damping. This type of insulator produces flexibility both horizontal and hysteretic damping.

In Fig. 24 is shown a bilinear hysteretic model which can be used for modeling a lead rubber bearing. Model parameters are the initial stiffness, K_u , secondary stiffness, K_d, and strength of flow, Q_d (Petrina, 2007)

$$K_d = C_{K_d}\left(K_r + K_p\right) , \tag{1}$$

$$K_u = \beta K_d , \tag{2}$$

$$Q_d(t) = Q_d \exp\left[-0.00897\left(t - t_0\right)\right] , \tag{3}$$

where: K_r is the lateral stiffness of the foot; K_p – additional stiffness of the plug lead; C_{K_d} – a way for change K_d ; t_0 – temperature before correction; t – temperature after correction; β – the ratio between K_u and K_d.

3.2. Friction Pendulum System

Unlike elastomeric bearing, the friction pendulum system (Fig.25) uses the features of a pendulum to extend the natural response of isolated structures to avoid the induction of strong forces in the structure (Fig. 26).

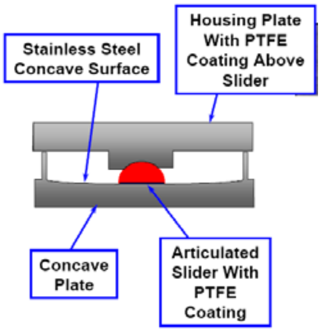


Fig. 25 – Friction pendulum system (Symans, 2009).

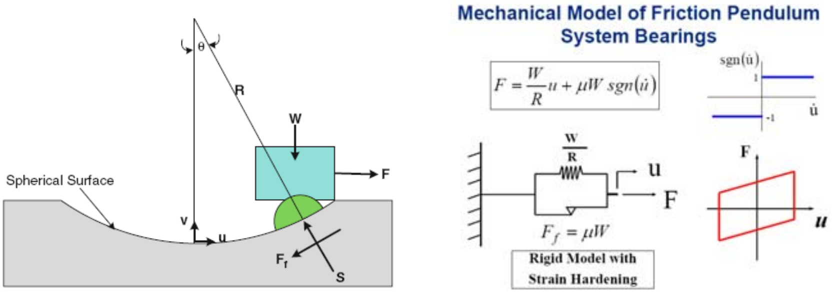


Fig. 26 – Mechanical model (Symans, 2009).

The insulator’s period is determined by simply choosing the radius of curvature of the concave surface. The torsional forces are minimized because the insulator’s center of the rigidity coincides with the structure’s center of mass and the restoring force is given by the stiffness, *k*. The benefits of the system are its ability to generate restoring forces due to its geometry, a simple numerical modeling, a linear stiffness of horizontal movement during moderate cyclical behavior repeatability, durability, maintenance of physical properties. One of the disadvantages of this type of bearing is represented by the large displacements which may be ocurr due to large earthquakes, and another disadvantage would be detaching on the surface due to its high tension/compressive strength (Calafell *et al*., 2008).

Equation of external force acting on the isolator is

$$F = \left(\frac{W}{R} \cos\theta \right) u + \frac{F_f}{\cos\theta} \,, \tag{4}$$

where: F is the external force; W – weight of the structure; R – radius of curvature of bearing; θ – rotation angle; F_f – friction force; u – horizontal components of displacement.

3.3. Tuned Mass Damper

Tuned mass dampers typically consist of an additional mass attached usually at the top of building where is the maximum movement, through an arch and a damping mechanism such as viscous or viscoelastic dampers (Fig. 27).

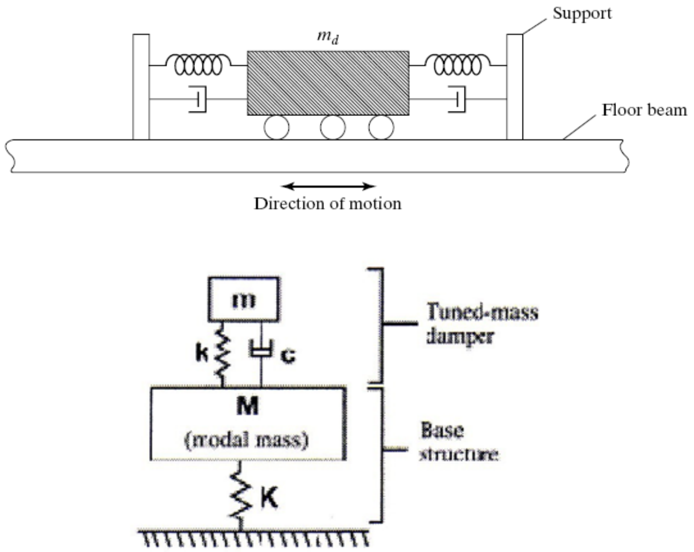


Fig. 27 – Mechanical model of tuned-mass damper.

Structure vibrations set in motion the tuned mass damper and the kinetic energy is transferred from the structure to the damper system. Usually the damping system depends on the ratio of the mass damper and the total mass of the building, the isolator weighs only 1.5%...2.0% of the total weight of the building which is normally sufficient to obtain a sufficient damping. The main advantages of this system are the possibility of adjusting the damper characteristics, easy maintenance, effective in mitigating the vibration caused by wind and earthquake. But most times there are restrictions of space which not allows installation of such a system and is necessary to install alternative isolation systems (Mociran, 2010).

The motion eqs. have the form
a) for the structure

$$\left(1+\overline{m}\right)\ddot{u}+2\xi\dot{u}+\omega^2 u=\frac{p}{m}-\overline{m}\ddot{u}_d \;; \tag{5}$$

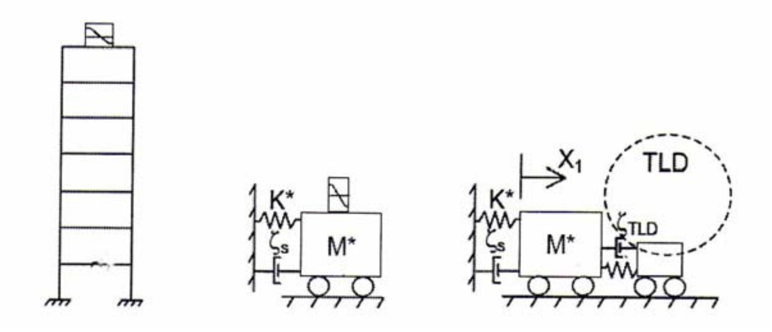
b) for the isolation system

$$\ddot{u}_d+2\xi_d\omega_d\dot{u}_d+\omega_d^2 u_d=-\ddot{u} \;, \tag{6}$$

where: m_d is the mass damper; k_d – damper stiffness; u_d– relative displacement between the damper and structure; u – relative displacement between structure and soil; a_g – ground acceleration; p – applied force structure; c_d – damping coefficient.

3.4. Tuned Liquid Damper

These dampers are made of rigid containers partially filled with liquid (Fig. 28). The principle of energy dissipation is similar to the control of mass damper, the fluid has the role of the mass and the restoring force is gravitational.



a *b* *c*

Fig. 28 – Mechanical model of tuned liquid damper (de Souza *et al.*, 2006).

Natural period of the damper can be easily adjusted by height and the size of water container. As benefits would be the simultaneous reduction of movement on two directions, low cost, easy maintenance, but as disadvantages it is necessary to use a larger volume in order to obtain the same damping as a tuned mass damper because during the earthquake a part of liquid does not move (Mociran, 2010).As a theoretical model we consider an U-shaped tube attached to the top of the cart, which contains a liquid mass, *m*, and density, ρ. The fluid in the middle of the tube is a hole whose opening can be adjusted to vary the resistance to fluid flow through this hole (de Souza *et al.*, 2006).

Motion eq. of the system is

$$(M+m)\frac{\mathrm{d}^2X}{\mathrm{d}t^2}+c\frac{\mathrm{d}X}{\mathrm{d}t}-k_1X+k_2X^3=\left[\frac{\mathrm{d}^2\varphi}{\mathrm{d}t^2}\sin\varphi+\left(\frac{\mathrm{d}\varphi}{\mathrm{d}t}\right)^2\cos\varphi\right]-\alpha m\frac{\mathrm{d}^2Y}{\mathrm{d}t^2}, \quad (7)$$

where: M is the table cart; m – liquid mass; X – cart movement; k_1, k_2 – stiffness; φ – angular rotation cart; Y – vertical direction of fluid movement.

3.5. Viscouselastic Dampers

The viscouselastic dampers (Fig. 29) usually use a polymer or rubber materials, that have large deformation under shear force to provide both energy dissipation and a restoring force; there damper are also very effective for a low vibration wind and moderate earthquakes. This type of device is made of steel plate between them finding viscouselastic material, and this device is being installed as part of a diagonal beams which can dissipate the energy of vibration through his action. It was demonstrated that these devices not only add damping and stiffness to the structure but increases the natural period of vibration of the structure. As a characteristic of this rubber but is that is usually temperature dependent. At high temperatures behaves like a soft spring and at low temperatures becomes hard and glassy (Matsagar & Jangid, 2005).

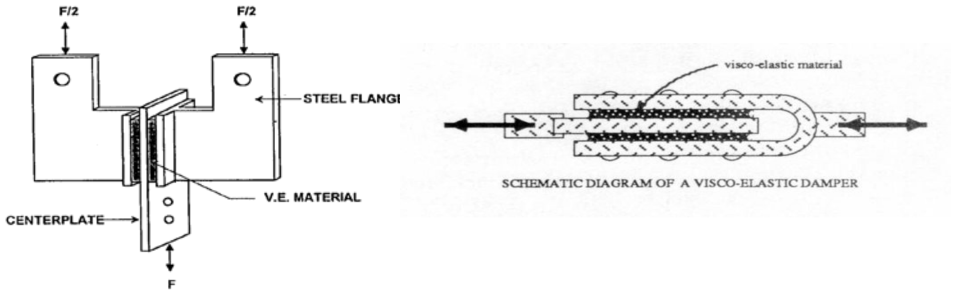


Fig. 29 – Viscouselastic dampers.

Fundamental dynamic characteristics are given by eqs.

$$C_{\mathrm{eq}}=\frac{\Delta W}{\pi\omega a^2}, \quad (8)$$

$$K_{d'}=\frac{A_s}{d}G', \quad (9)$$

where: C_{eq} is the damping coefficient; ΔW – disipated energy; ω – circular frequency; f – frequency; a – amplitude; $K_{d'}$ – equivalent stiffness; A_s – shear area; d – shear thickness; G' – storing modulus.

3.6. Kinematic Insulators (Pinochet *et. al*., 2006)

The characteristics of this insulator are the reducing the base shear force, interstory drift and the floor acceleration, better than the friction pendulum system.

It is developed by Pinochet *et al*. (2006) and it is considered as an economical method of seismic isolation. It can be used as a foundation pile, in areas where soil is poor, with a central prestressed cable and rolling steel surfaces at the bottom and the top ends. Energy dissipation occurs by yielding unbonded ductile bars but also to friction between the reinforcing central pile and the walls of the pile. An association with friction pendulum system consists of the uplift of the structure caused by strong tension/compression forces, which is more significant in case of a rolling surface rather than a spherical surface. Another consideration would be to verify that the tension in the prestressed bars does not exceed the maximum admissible tension (Fig. 30).

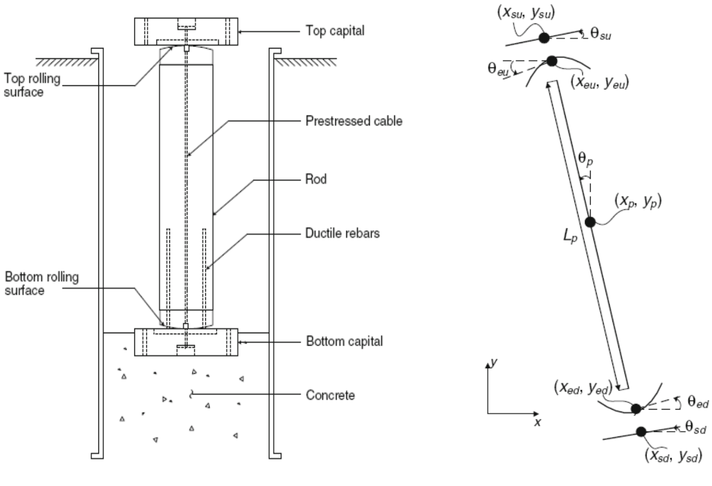


Fig. 30 – Kinematic isolators (Calafell *et al*., 2008).

Restoring force of the isolator is given by eq.

$$Q_i = V_{qi}^T + L_d^T\left(V_{qd}^T - Q_d\right) + \left(G_{qi}^T + L_d^T G_{qd}^T\right) f_n(q_n, z), \tag{10}$$

where: V_{qi} , V_{qd} are inertial energies; L_d^T – transformation matrix between independent and dependent coordinates; Q_d – vector forces; G_{qi} , G_{qd} – components of a vector that causes acquired deformability.

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SISTEME DE IZOLARE SEISMICĂ
Clasificare, proprietăţi şi utilizare

(Rezumat)

Izolarea seismică are ca scop protejarea structurilor de hazarde naturale şi nu numai. În clădirile flexibile se pot produce vibrații excesive datorită acțiunii vântului afectând astfel confortul locuitorilor dar şi sistemul structural. Pentru a asigura performanțele funcționale ale structurilor s-au adoptat mai multe măsuri de reducere a răspunsului structural, prezentate în această lucrare, inclusiv o discuție referitoare la sisteme auxiliare de amortizare, precum şi exemple recente ale utilizării acestora în diferite țări precum Statele Unite, Japonia, Turcia, Italia.