VISCOUS DAMPING FOR BASE ISOLATED STRUCTURES

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ABSTRACT

Seismic Base Isolation can use elastomeric pads, sliding plates or inverted pendulums. Each method can include an energy dissipation means, but only as some kind of hysteretic damping. Hysteretic damping has limitations in terms of energy absorption and may tend to excite higher modes in some cases..

It's possible to avoid these problems with viscous dampers. Viscous damping adds energy dissipation through loads that are 90^{o} out of phase with bending and shear loads so even with damping levels as high as 40% of critical adverse side effects tend to be minimal.

This paper presents basic theory of viscous damping, and also describes a sample project. Viscous dampers being built for the new San Bernardino Medical Center reduce both deflections and loads by 50% compared with high damping elastomer base isolation bearings by themselves.

INTRODUCTION

Base isolation systems for large structures have been in use for many years, with some base isolators dating back to the early 1900's. Base isolation bearings for an isolated structure mount between the structure and its foundation. The isolation bearings permit relative transverse motion between the structure and the ground while providing rigid support in the vertical direction. The flexibility between the structure and the ground reduces structural response under seismic shaking.

There are three main forms of base isolation systems currently in use; flat plate sliding bearings, friction pendulum sliding bearings, and elastomeric bearings. These three types of base isolators are shown in Figures 5, 6 and 7 along with their force/stroke characteristics. All three types of isolators are effective, yet each one has limitations. Their main limitation is that none of these isolators can consistently provide the high degree of energy dissipation needed in many current applications. Moreover, when these three types of isolators are designed for maximum energy dissipation, their action typically involves sudden changes in force level, which tends to excite higher structural modes. In addition, the friction inherent in sliding element bearings could create significant residual displacement after an earthquake.

The addition of fluid viscous elements to any base isolation system can greatly improve performance. This type of element has a damping force that is proportional to the relative end velocity raised to the power "n," where "n" can have any value from .4 to 1.95. By adding viscous elements it is possible to increase damping to as much as 40% of critical, which significantly decreases bearing displacements during an earthquake. Forces and accelerations within a structure are also reduced in most cases, since the output force from the viscous elements is inherently out of phase with structural bending and base shear stresses. At the same time residual offset is greatly reduced, as the isolation bearings themselves can be designed with minimum friction.

The end result is significantly improved performance, often with a reduction in overall cost. The addition of viscous dampers markedly reduces dynamic displacement, which lessens both the size and the cost of the base isolation bearings, and also reduces the amount of ductile detailing which would otherwise be required in the structure. Smaller relative displacement also means less costly flexible walkways and ducts between separately isolated parts of the structure. Considering all these factors, a structural system that incorporates viscous dampers often costs less than the same system without viscous elements.

A series of tests on base isolated structures with and without viscous dampers (Constantinou et al., 1992, 1993) showed that fluid dampers with an "n" value of 1.0 reduced story drifts by 30% to 70%, and also reduced story shear forces by 40% to 70%.

SUMMARY

The next section of this paper describes the analytical model used to predict performance of the three base isolation systems both with and without viscous dampers. A following section describes the fluid viscous dampers and how they work. This is followed by a description of a hybrid fluid viscous element with restoring force capability. This is the kind of fluid viscous element that performs well in combination with flat sliding plate bearings.

The next three sections describe the three types of base isolation systems; flat sliding plate, friction pendulum and elastomeric element. These sections also describe how viscous damper can significantly improve the performance of all three systems. This is followed by a section on the cost of typical viscous dampers.

The last part of this paper gives several case studies showing the use of base isolation systems in conjunction with elastomeric base isolation bearings. These examples include the new San Bernardino Medical Center, which is under construction, and the Los Angeles City Hall. The Los Angeles City Hall uses viscous dampers in two locations; in parallel with the elastomeric base isolators, and as part of a structural bracing system below the 27th story.

ANALYTIC MODEL

Earthquake Inputs

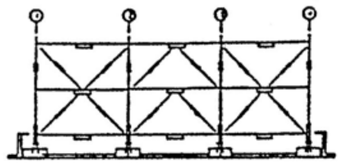
All three of the base isolation systems described in this paper are compared in terms of their performance under five earthquake shaking inputs; El Centro (1940), Northridge (1994) Sylmar County Hospital Parking Lot (PGA 0.89g), Northridge (1994) Santa Monica City Hall (PGA 0.90g) and San Fernando (1971) Pacoima Dam (PGA 1.20g). In all cases the particular input selected is one of the most severe. PGA is Peak Ground Acceleration.

Building Model

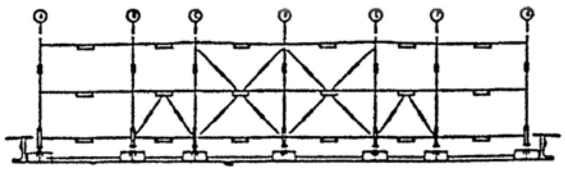
All three types of base isolation systems were modeled as supporting a generic two story structure. This building model is representative of several existing base isolated buildings in Southern California. The building that was modeled has the following properties:

Number of Stories:	2
Floor Area:	14,000 square feet
Soil Conditions:	UBC Type S1 (Stiff)
Structural System:	Steel floor framing with concrete fill. Steel braced frame, 28 columns, each supported by an isolator
Seismic Weight:	1st Floor = 1700 kips 2nd Floor = 1675 kips 3rd Floor = 2300 kips Roof = 2300 kips (including equipment) Total = 5675 kips
Fixed Base Period:	0.25 seconds E-W or N-S

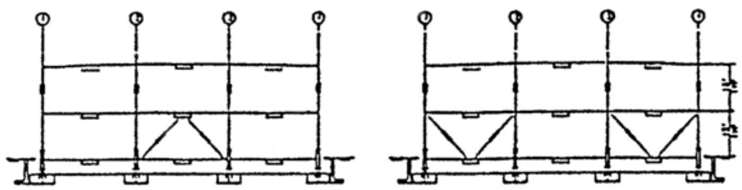
Figure 1 shows a picture of the structure model used in the analysis.



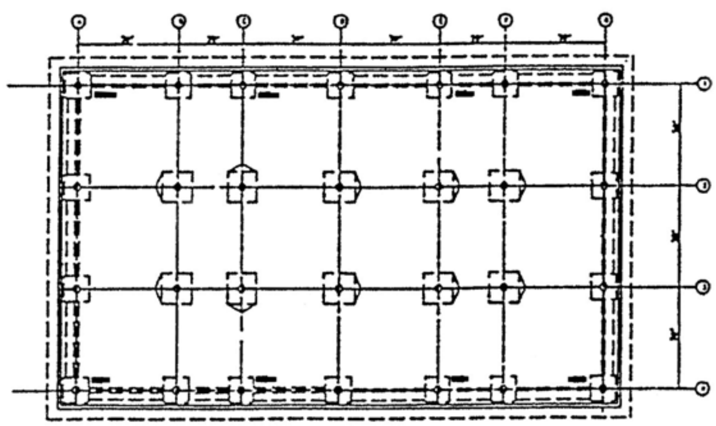
Typical Transverse Exterior Frame



Typical Longitudinal Exterior Frame



Typical Transverse Interior Frame



Plan

▬ Indicates Location of Viscous Dampers

Structural Plan and Frame Elevations

FIGURE 1
DYNAMIC MODEL

Base Isolation Systems
Three different isolation systems have been analyzed in conjunction with the building model just described; high damping (bi-linear) elastomer bearings, low damping elastomer bearings, and sliding systems with a linear restoring force. This sliding system analysis applies to both the friction pendulum system and the flat plate sliding bearing with added spring elements. Here are the parameters used for these analyses:

Bilinear Model:

Initial Stiffness (k_1)	=	16.19 kips/inch
Second Stiffness (k_2)	=	2.94 kips/inch
Yield Force (Fy)	=	21.05 kips
Effective stiffness (k_{eff})	=	4.02 kips/inch @ 16 in.

Linear Model:

Effective stiffness (k_{eff})	=	4.02 kips/inch @ 16 in.

Sliding Model:

Max. Coeff. of Friction (μ_{max})	=	0.07
Max-Min Coeff of Friction ($\Delta\mu$)	=	0.045
Constant (α)	=	0.90
Yield Displacement (Δy)	=	0.10 inch
Global Spring Force	=	77.0 kips/inch

It should be noted that these parameters represent typical values. They have not been optimized for performance. They serve as a good representation of base isolation systems for the intended purpose, and also as a good basis of comparison of base isolation systems with and without supplemental viscous damping.

Viscous Damper Model
The supplementary viscous dampers are modeled as linear viscous dampers, where damping output is proportional to velocity times a constant, C. In this case C=1.45 kip/ips, giving a maximum damping force of 100 kips at a velocity of 70 ips. There are eight dampers on the perimeter of the building. The eight dampers provide viscous damping that is equivalent to approximately 14% of critical. It is possible that other values of damping would provide even better performance than the results shown.

Figure 2 shows a typical fluid viscous damper for use in conjunction with base isolation systems.

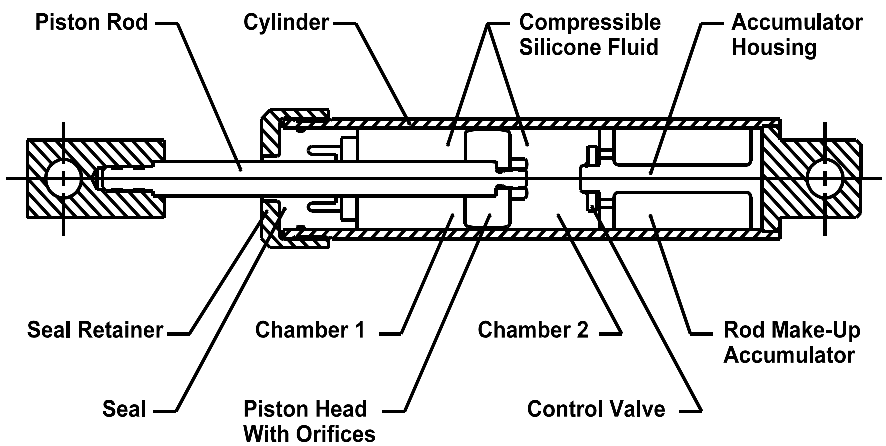


FIGURE 2
FLUID VISCOUS DAMPER

VISCOUS DAMPER DESCRIPTION

The viscous damper for structures outwardly resembles the shock absorber on an automobile, but operates at a much higher output. Base isolation dampers are significantly larger than automotive dampers, and are constructed of stainless steel and other extremely durable materials as required to furnish a life of at least 40 years. The damping fluid is silicone oil, which is inert, non-flammable, non-toxic, and stable for extremely long periods of time. The seals in the viscous damper are a patented high technology design based on aerospace fluid elements, and provide totally leak free service. This design has been proven through rigorous testing and has been in use for over 40 years.

The damping action is provided by the flow of fluid across the piston head. The piston head is made with a deliberate clearance between the inside of the cylinder and the outside of the head, which forms an annular orifice. The fluid flows through this orifice at high speed as the damper strokes. The shape of the piston head determines the damping characteristics. The force/velocity relationship for this kind of damper can be characterized as $F=CV^n$, where F is the output force in pounds, V is the relative velocity across the damper in inches per second, C is a constant determined mainly by the damper diameter and the orifice area, and n is a constant exponent which can be any value from .40 to 1.95. The exact value for n depends upon the shape of the piston head.

The analytical results reported here use a value of “n” of 1.0. It has been found that “n” values closer to .5 often produce significantly better results. This is the value that has been incorporated in the San Bernardino Medical Center dampers. Constantinou reports reductions in displacement of 20% and reductions in total force of 10% by changing “n” from 1.0 to 0.5.

As the orifice is provided by the annular clearance between the piston head and the cylinder body, it is possible to provide inherent thermal compensation by making these two parts from different materials. By choosing materials with the correct thermal coefficients of expansion, it is possible to make the variation in the gap compensate for the variation in fluid properties as temperature changes.

A series of tests was conducted at NCEER on Taylor Devices dampers with intrinsic thermal compensation (Constantinou et al., 1992, 1993). It was found that the temperature range of 32^{o}F to 122^{o}F produced a change in damping from +44% to -25%, which is relatively small. Subsequent design improvements have resulted in even less variation in damping characteristic over a similar temperature range. For instance, total force tolerance band on the dampers produced for the new San Bernardino Medical Center is +/-15% over a similar temperature range, including the effects of tolerance variation.

HYBRID FLUID VISCOUS DAMPER WITH RESTORING FORCE

The hybrid fluid viscous damper with restoring force uses the same viscous damping action as the basic damper described in the previous section, with the addition of compression spring action and a mechanical cage and yoke mechanism to provide centering action in both the tension and compression directions, while also providing bi-directional damping.

The main element of the hybrid damper is the fluidicshok cartridge, shown in Figure 3A. This element is similar to a hydraulic cylinder with no ports. As there is no way for the fluid to get out, fluid pressure builds rapidly when the piston rod pushes into the cylinder. This causes a strong spring action.

During compression of the damper, fluid must flow around the piston head at high velocity, similar to the damper just described. This causes a strong damping action in addition to the spring action. This same kind of damping action occurs during extension. During compression the damping action adds to the spring force. During extension it subtracts from the spring force, forming a hysteresis loop.

Figures 3B, 3C and 3D show how structural elements are added to the fluidicshok cartridge to form the complete tension/compression liquid spring damper. Figure 4A shows how this element works in tension and in compression.

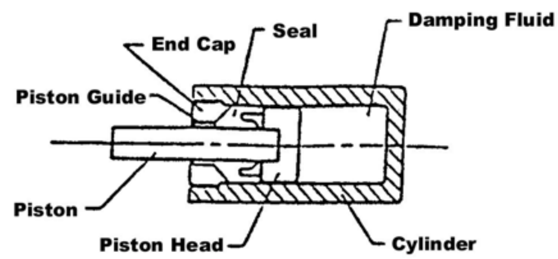


FIGURE 3A
FLUIDICSHOK CARTRIDGE

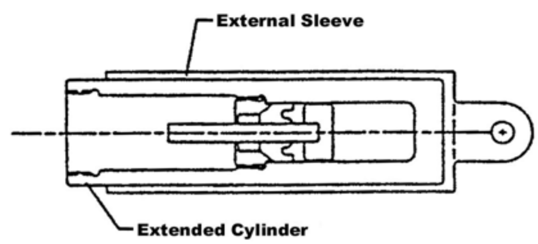


FIGURE 3B
TENSION-COMPRESSION ISOLATOR DESIGN

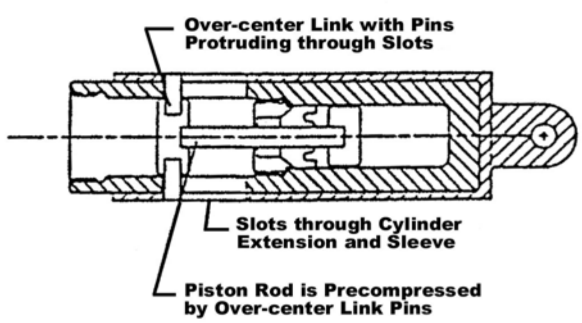


FIGURE 3C
ADD OVER-CENTER LINK, SLOTS, PRECOMPRESSION

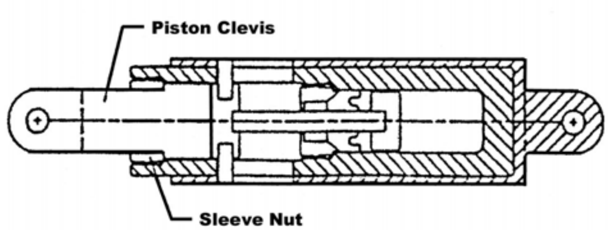


FIGURE 3D
ADD PISTON CLEVIS / SLEEVE NUT

The end result is the force/stroke characteristic shown in Figure 4B. Here are the important elements of this characteristic

- There is a strong centering action. The element acts just like a rigid beam until its preload is exceeded.
- There is a strong spring action. When moved slowly, the element behaves just like a powerful preloaded spring that wants to return the structure to its neutral position.
- There is a high damping, enough to absorb significant amounts of earthquake energy.
- The action is the same in both the tension and the compression directions.

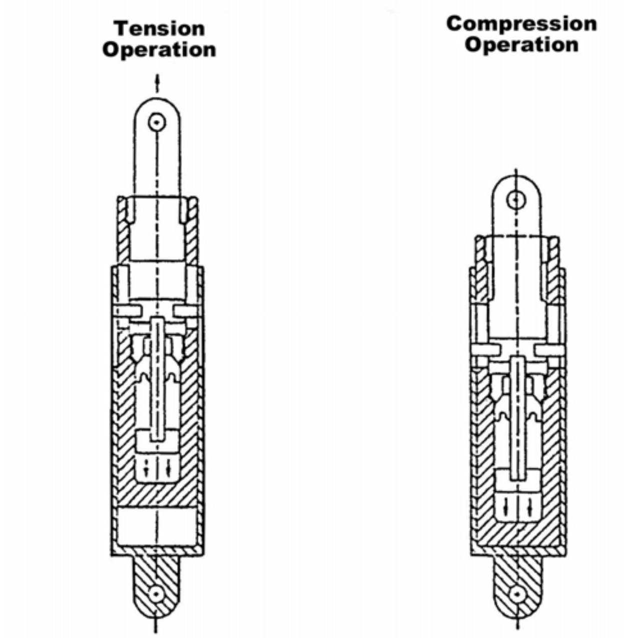


FIGURE 4A
TENSION AND COMPRESSION OPERATION

The hybrid fluid viscous damper with restoring force can provide maximum force up to 2,000 Kips. Its spring rate, preload, damping constant and damping exponent can be adjusted to optimize performance in a particular structure. When a system of hybrid fluid dampers is added to a set of flat sliding plate bearings, the resulting isolation system performs extremely well and often costs less than other isolation systems to do the same job.

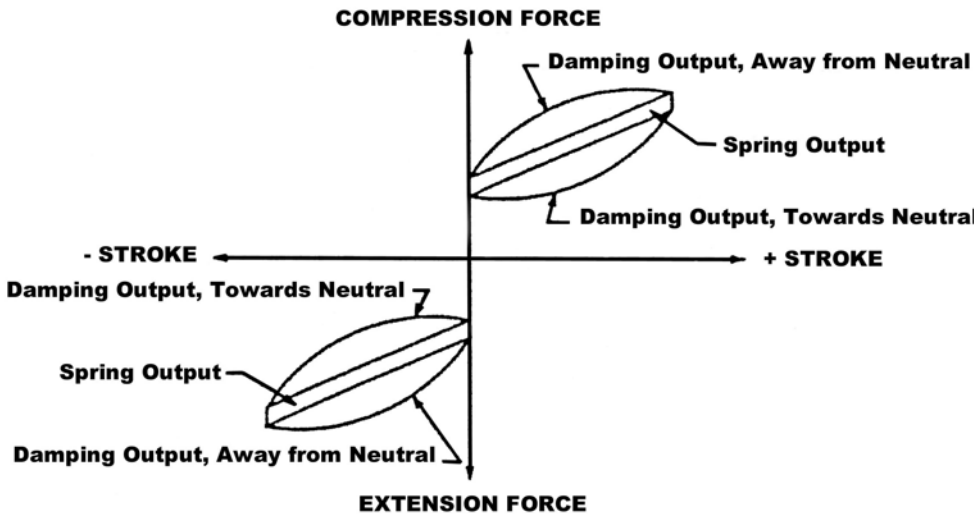


FIGURE 4B
OPERATIONAL OUTPUT

SLIDING PLATE BEARINGS

Flat plate sliding bearings have been used in many applications to support bridge structures and permit thermal distortion. This kind of bearing has no inherent centering action, so the isolated structure can end up with considerable residual displacement after the earthquake is over. The structure may have to be forced back to its original position with hydraulic jacks.

Until now this kind of bearing has very seldom been used as a structural base isolator, due to its large and relatively unpredictable residual offset after an earthquake. However, this type of isolator is the least expensive of the three types discussed in this paper, and has the advantage of being relatively insensitive to uplift, as discussed a little later.

A typical sliding plate bearing is shown in Figure 5. It consists of a stainless steel plate that attaches to the foundation and a Teflon impregnated pad that attaches to the bottom of the isolated structure. The arrangement can also be inverted, with the Teflon impregnated pad carried on the foundation and the stainless steel plate attached to the underside of the structure. This inverted arrangement tends to protect the large sliding surface from moisture. Bearings of this type are available from the D.S. Brown Co.

The main advantages of the sliding plate base isolation system are its low cost and its excellent service history in bridges. In addition it is able to function in the presence of moderate amounts of uplift. The isolated structure can pull away from the bearing and then settle back down with no other deleterious effect than the loss of frictional force during the time of separation and possible damage due to the impact. It is possible to add compression fluid viscous dampers in the vertical support system for the bearing pads to insure against impact damage when the bearing comes back together.

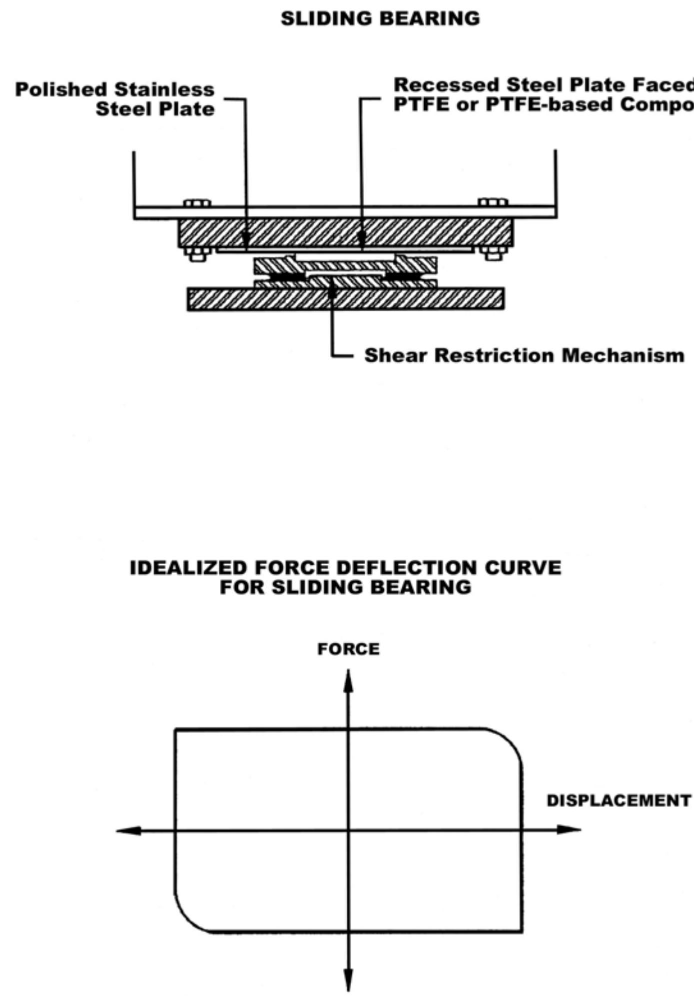


FIGURE 5
TYPICAL SLIDING PLATE BEARING

The main disadvantages of the sliding plate bearing system is the lack of centering action, and the lack of damping. Variations in friction due to temperature changes and long term environmental subjection are also concerns. Since the friction force depends on the vertical loading, accurate and predictable analysis results may be difficult to achieve. Also, sliding plate bearings have a limited history in building projects, particularly in this country.

While it is possible to provide energy dissipation in the sliding plate bearing by using a high friction material for the bearing pad, the resulting hysteresis causes abrupt changes in the forces applied to the isolated structure whenever the velocity changes direction. This in turn tends to excite the higher modes of the structure, with adverse effects.

Typical friction values for sliding plate bearings range from a low of .04 to a high of .15. The higher the friction the more energy dissipation, so the lower the displacement under earthquake shaking. However, higher friction increases the excitation of higher modes in the isolated structure, and also increases the likelihood of high residual displacement. This dilemma can be completely eliminated by adding fluid viscous dampers in series with the sliding plate bearings. As described elsewhere in this paper, the viscous damping provided by fluid viscous devices smoothly varies with velocity, and minimally excites the higher modes of a structure. Moreover the amount of damping available is much higher than the equivalent of a frictional coefficient of 0.15.

It is also possible through the addition of hybrid fluid damper elements (described earlier) to provide centering action for the sliding plate bearings. This particular kind of element has a very strong centering action, strong enough to return the isolated structure to its original position after an earthquake. The centering action of the hybrid damper can be designed to overcome the friction of the sliding plate bearing and provide near-exact re-entering.

Table 1 shows the results of a sliding system for the four earthquakes that were analyzed, both with and without supplementary viscous damping. Under worst earthquake conditions the viscous dampers cut the maximum deflection almost in half, and reduced maximum g's by around 25%. Note that these results apply to both the sliding plate bearing with spring centering, and to the friction pendulum system described in the following section.

Sliding plate bearings inherently provide excellent performance at low cost. When fluid elements with viscous damping and spring action are added to a flat sliding plate bearing system, overall function of the system can be comparable under most conditions to any other type of base isolation method. Cost for such a system tends to be low compared to competing systems.

FRICTION PENDULUM BASE ISOLATOR

The friction pendulum base isolator is shown in Figure 6 along with its characteristic force-displacement loop. Note that this type of isolator has a centering action, caused by the horizontal component of reaction in the dish to the vertical gravity force. This horizontal component increases with travel away from center, providing the same effect as a linear spring.

There is also energy dissipation, due to the friction between the spherical pad and the dish surface. This friction can range from .04 to .15, just like in the flat plate sliding bearing.

The lower the friction the better the centering action of the friction pendulum isolator. However, higher friction is desirable to increase energy dissipation, which reduces dynamic displacement under earthquake shaking. But higher friction increases the tendency to excite higher modes in the isolated structure due to the abrupt change in loading as the velocity reverses direction. The design of any friction pendulum base isolation system is always a compromise between the need for low friction to minimize residual offset and higher mode excitation, and the need for high friction to minimize dynamic displacement.

TABLE 1

Earthquake	PGA	Sliding System (FPS or Sliding Plate)							
		Max Base Shear (K) Resultant		Story Shear to Base Shear Ratio		Max RESP (G's)	Max Displacement at Center of Mass of Base (in.)		
		Above B.I.L.	Below B.I.L.	Story 2	Story 1		X	Y	Resultant
El Centro		368.036	527.276	0.403	0.295	0.09	0.00	2.58	2.58
Sylmar Co. Hospital Pkg. Lot	0.89	1730.57	2457.28	0.242	0.177	0.43	-21.19	-17.96	27.78
Santa Monica City Hall Record	0.90	657.772	862.553	0.335	0.245	0.15	-0.592	3.762	3.80
1971 Pacoima Dam Record	1.20	1126.00	1576.01	0.224	0.164	0.28	-14.83	-7.116	16.44
Earthquake	**PGA**	**Sliding System (FPS or Sliding Plate) with Viscous Dampers**							
		Max Base Shear (K) Resultant		**Story Shear to Base Shear Ratio**		**Max RESP (G's)**	**Max Displacement at Center of Mass of Base (in.)**		
		Above B.I.L.	**Below B.I.L.**	**Story 2**	**Story 1**		**X**	**Y**	**Resultant**
El Centro		388.675	556.846	0.403	0.295	0.10	-0.002	2.113	2.11
Sylmar Co. Hospital Pkg. Lot	0.89	1305.46	1820.21	0.223	0.163	0.32	-14.10	-4.639	14.84
Santa Monica City Hall Record	0.90	850.586	1089.93	0.365	0.267	0.19	-0.371	2.497	2.52
1971 Pacoima Dam Record	1.20	1245.20	1667.03	0.22	0.161	0.29	-12.26	-6.058	13.67

TABLE 2

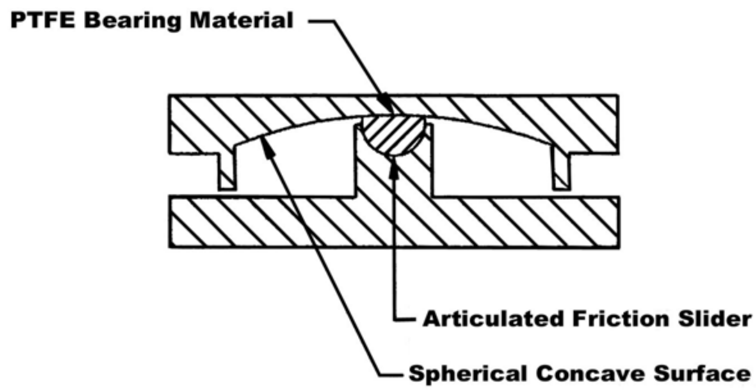
Earthquake	PGA	High Damping Rubber							
		Max Base Shear (K) Resultant		Story Shear to Base Shear Ratio		Max RESP (G's)	Max Displacement at Center of Mass of Base (in.)		
		Above B.I.L.	Below B.I.L.	Story 2	Story 1		X	Y	Resultant
El Centro		535.99	767.89	0.403	0.295	0.13	0.00	3.574	3.57
Sylmar Co. Hospital Pkg. Lot	0.89	1787.83	2526.75	0.23	0.169	0.44	-16.06	-15.54	22.34
Santa Monica City Hall Record	0.90	678.03	948.43	0.343	0.251	0.17	0.017	5.408	5.40
1971 Pacoima Dam Record	1.20	1280.63	1789.93	0.235	0.172	0.31	-14.24	-7.532	16.11
Earthquake	**PGA**	**High Damping Rubber with Viscous Dampers**							
		Max Base Shear (K) Resultant		**Story Shear to Base Shear Ratio**		**Max RESP (G's)**	**Max Displacement at Center of Mass of Base (in.)**		
		Above B.I.L.	**Below B.I.L.**	**Story 2**	**Story 1**		**X**	**Y**	**Resultant**
El Centro		529.50	758.60	0.403	0.295	0.13	0.00	3.02	3.01
Sylmar Co. Hospital Pkg. Lot	0.89	1420.36	1638.74	0.284	0.208	0.29	-13.11	-4.927	14.00
Santa Monica City Hall Record	0.90	707.04	998.47	0.319	0.234	0.18	0.161	3.443	3.44
1971 Pacoima Dam Record	1.20	1345.74	1836.70	0.225	0.165	0.32	-11.83	-6.275	13.38

TABLE 3

Earthquake	PGA	Low Damping Rubber							
		Max Base Shear (K) Resultant		Story Shear to Base Shear Ratio		Max RESP (G's)	Max Displacement at Center of Mass of Base (in.)		
		Above B.I.L.	Below B.I.L.	Story 2	Story 1		X	Y	Resultant
El Centro		1320.83	1892.32	0.403	0.295	0.33	0.00	-11.46	11.45
Sylmar Co. Hospital Pkg. Lot	0.89	4294.29	6108.77	0.247	0.18	1.07	29.25	8.977	30.59
Santa Monica City Hall Record	0.90	1530.93	2182.81	0.321	0.235	0.38	-4.349	9.684	10.61
1971 Pacoima Dam Record	1.20	3428.81	4832.77	0.194	0.142	0.85	-25.54	-13.93	29.09
Earthquake	**PGA**	**Low Damping Rubber with Viscous Dampers**							
		Max Base Shear (K) Resultant		**Story Shear to Base Shear Ratio**		**Max RESP (G's)**	**Max Displacement at Center of Mass of Base (in.)**		
		Above B.I.L.	**Below B.I.L.**	**Story 2**	**Story 1**		**X**	**Y**	**Resultant**
El Centro		572.53	830.24	0.403	0.295	0.14	0.00	4.772	4.77
Sylmar Co. Hospital Pkg. Lot	0.89	2554.78	3568.85	0.209	0.153	0.63	-17.91	-6.371	19.01
Santa Monica City Hall Record	0.90	995.05	1419.95	0.34	0.249	0.25	-1.419	7.108	7.24
1971 Pacoima Dam Record	1.20	2161.93	3011.72	0.181	0.132	0.53	15.67	7.76	17.48

The addition of fluid viscous elements in parallel with the friction pendulum elements completely solves this difficulty. The viscous damping elements can provide up to 40% of critical damping while at the same time reducing residual offset, and without exciting any higher modes. They permit the friction pendulum elements to operate at 4% friction, which is the minimum value that can be realistically maintained.

SECTION VIEW OF AN FPS CONNECTION



IDEALIZED FORCE DEFLECTION CURVE FOR FPS BEARING

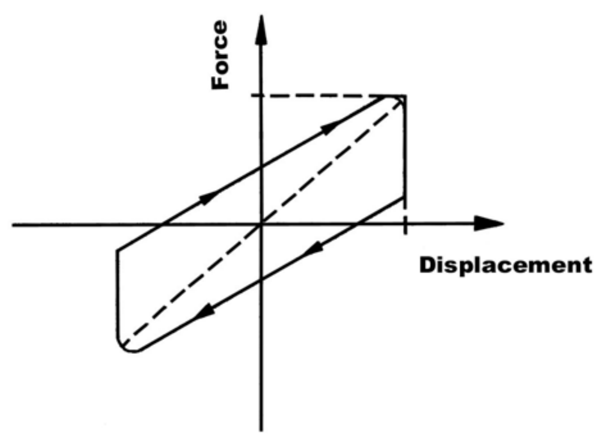


FIGURE 6
FRICTION PENDULUM BASE ISOLATOR

Table 1 shows the results of a friction pendulum system for the four earthquakes that were analyzed, both with and without supplementary viscous damping. These are the same results as for the sliding plate system with centering springs. Under worst earthquake conditions the viscous dampers cut the maximum deflection almost in half, and reduced maximum g's by around 25%.

Friction Pendulum Bearings are available from Earthquake Protection Systems.

ELASTOMERIC PAD BASE ISOLATORS

Elastomeric base isolation bearings have been in use for at least the past 30 years, and originated in New Zealand. As shown in Figure 7, they consist of a large number of thin layers or "pancakes" of rubber interspersed with metal plates. The entire sandwich of rubber disks and metal plates is bonded together.

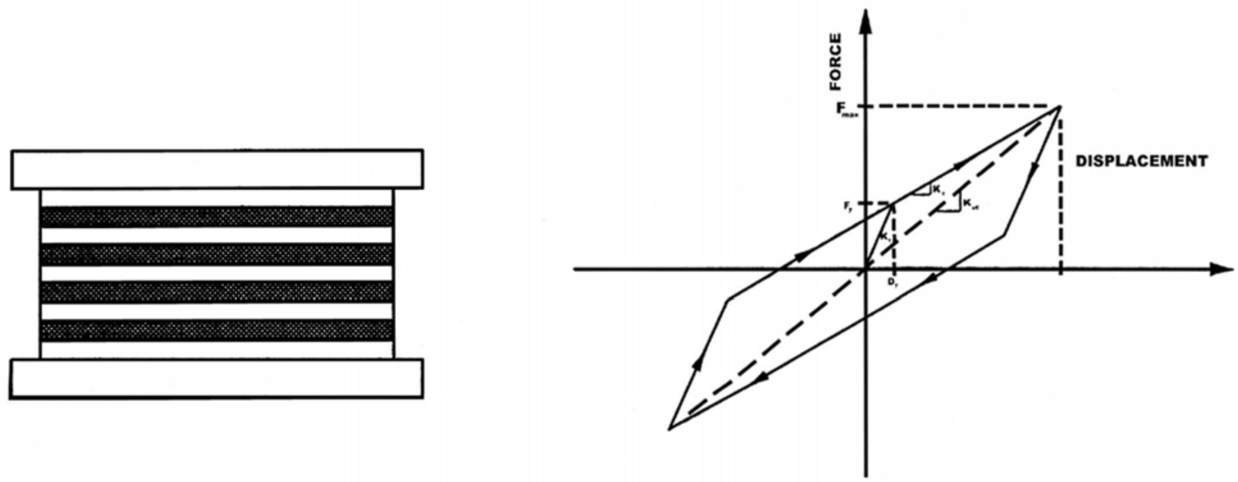
When correctly manufactured, this type of bearing can support lateral motions up to twice the height of the bearing. Actual design displacements will vary depending upon the vertical load on the bearing and the end attachment details.

Until recently elastomeric base isolators were made from natural rubber or similar low damping elastomeric material. This material is very reliable, and has a long and successful history. As it has very little damping, relative displacement under earthquake input can be high. When used for structures subjected to the Loma Prieta or the Northridge earthquake within approximately five miles of the epicenter, the displacement for low damping rubber base isolators can exceed the capacity of most practical bearings. Under these conditions the displacement of structures supported on low damping elastomeric bearings can be as high as +/- four feet.

As more accurate estimates of earthquake shaking have become available, it has become clear that some form of damping is needed to limit displacements to values that can be handled by the elastomeric bearings. This has led to the development over the last ten years or so of "high damping" elastomeric pad bearings, which have typical damping values in the range of 15% of critical. Lead-Rubber bearings, patented by DIS, also provide high damping. In these bearings a lead core is installed inside of low damping or natural rubber to provide hysteretic damping which can be as high as 30% of critical.

It should be understood that the type of damping inherent in all elastomeric bearings is not viscous damping, but is instead the hysteretic damping produced by differential spring rate.

The shear spring rate for a high damping elastomeric pad is high until it reaches its predetermined "yield point," as shown in Figure 3. This bi-linear behavior is a function of the particular type of elastomer material or the yielding of the lead core, and does not indicate degradation of the material at deflections beyond the predetermined "yield point." The area enclosed by the force deflection curve as the isolator travels away from center and then back is the amount of energy dissipation per half cycle. Depending upon the type of the bearing, there may be a fairly sudden change in force level whenever the displacement changes direction, which may tend to excite the higher modes in the isolated structure. The likelihood for this happening is not as high in elastomeric bearings as it is in friction type bearings.



Elastomeric Pad

Idealized Force Deflection Curve For Elastomeric Bearings

FIGURE 7
ELASTOMERIC BASE ISOLATION BEARINGS

High damping rubber isolation bearings have some possible disadvantages. First, not all of the different high damping materials have the long success history of the low damping bearings. Second, it has sometimes turned out to be difficult in practice to achieve the 15% of critical damping in particular high damping rubber bearing designs, particularly at displacements near the capacity of the bearing. A third problem is that some high damping rubber compounds may be sensitive to changes in temperature, and may tend to display significant variations in stiffness properties as they go through their first few cycles. These problems are less significant with lead-rubber bearings which use mostly natural rubber compounds. However, deterioration of the lead-rubber assembly as it goes through several high displacement cycles also poses a potential problem.

Another potential issue with elastomeric bearings is that their performance under uplift conditions is not known. All testing of elastomeric bearings until now has been under compression loading only. However, under severe dynamic load conditions a relatively tall isolated structure sometimes has portions of its base that may rise vertically and pull on the supporting bearings. In cases where elastomeric bearings are firmly attached to both the ground and to the isolated structure the bearings can go into tension under uplift conditions. This has been a significant problem with some of the designs using elastomeric pads. One attempt to alleviate this problem uses stud mounting rather than bolted connections for the isolators. This eliminates problems with tension in the isolators, but may cause other problems of structural detailing and potential instability. Elastomeric bearings have been shown to have significant tension capacity, but more research is needed before such isolators can be designed and tested for use in tension on actual projects.

The addition of fluid viscous dampers to a set of elastomeric base isolation pads greatly enhances their performance. The first and most significant effect is to cut down on dynamic displacement, possibly by as much as 50%. There is an associated reduction in base shear by the same amount, which means lower forces and accelerations in the isolated structure. The reduction in dynamic displacement provided by the addition of viscous dampers permits the elastomeric pads to be significantly smaller, and hence less costly and more practical to design and build. It is not uncommon for a combination of viscous dampers and elastomeric pads, optimized for performance, to be less costly than the elastomeric pads would have been without the dampers.

A secondary advantage from the addition of dampers is that the subsequent reduction in displacement and base shear reduces the tendency for uplift. Less of the structure is subject to uplift, and the uplift in the remaining structure is less. Also, if uplift does occur, 100% of the damping force still exists in the viscous dampers, even though the elastomeric bearings may have lost damping capacity due to the loss of compressive force which enhances isolator damping.

A third and most significant advantage of using viscous damping elements in conjunction with elastomeric pads is that the pads can now be made from natural rubber or other low damping material, a design which has been proven over many years of use.

Table 2 shows analysis results for high damping elastomer bearing systems for the four earthquakes analyzed, both with and without supplementary viscous damping. Under worst case earthquake shaking the addition of viscous dampers reduced displacement by 37% and reduced maximum g level by 34%. It is important to note that the viscous dampers were not optimized, but were simply representative of what might be used. It is expected that optimization would show even better performance improvement.

Table 3 shows analysis results for low damping elastomer bearing systems for the four earthquakes analyzed, both with and without supplementary viscous damping.

Under worst case earthquake shaking the addition of viscous dampers reduced displacement by 38% and reduced maximum g level by 41%. Again, it is important to note that the viscous dampers were not optimized, but were simply representative of what might be used.

Engineered Elastomeric Isolation Bearings are available from several sources, such as Dynamic Isolation Systems and Bridgestone Engineered Products Co.

COST INFORMATION

As mentioned earlier, the cost of an isolation system containing viscous dampers is often less than the cost of a similar isolation system without dampers. The reason for this is that the addition of viscous dampers reduces the dynamic displacement by as much as 50%, which greatly reduces the cost and size of the isolation pads. This is true whether the isolation pads be Flat Sliding Plates, Friction Pendulums, or Elastomeric Bearings.

The cost of viscous dampers ranges from around $1000 each for a 10 kip +/- 2.0 inch stroke damper to over $60,000 each for a 1,000 kip +/- 24 inch stroke damper. As an example, 325 kip; +/- 24 inch stroke dampers in quantities of 100 or more have cost $21,000 each. 50 kip +/- 2.0 inch stroke dampers in quantities of 100 or more have cost $2,000 each.

The exact cost of a damper depends on a number of factors such as the kind of end fittings, and the relative velocity at maximum loads. Many applications require the use of spherical end fittings, which slightly increases the cost. Other applications permit the use of threaded stud ends, which reduces the cost.

In some cases end brackets can be supplied with the dampers. In general a pair of end fittings will cost from 10 to 15% of the cost of the dampers themselves.

TYPICAL DAMPER INSTALLATIONS

Fluid Viscous Dampers are currently shown on a number of major projects, such as the replacement San Bernardino Medical Center, which is a set of five new buildings, and the earthquake refurbishment of the Los Angeles City Hall.

San Bernardino Medical Center Replacement Project

The new San Bernardino Medical Center located in Colton, California, consists of five separate buildings. This complex is near the intersection of two major faults. All five buildings are isolated on high damping elastomer pads in conjunction with large Fluid Viscous Dampers. These particular dampers are now in construction.

Figure 8 shows the Nursing Tower, which is the largest of the five buildings. Figure 9 shows a typical installation of the dampers underneath the building and Figure 10 shows the location in plan view of the dampers for this particular structure.

FIGURE 8
SAN BERNARDINO MEDICAL CENTER NURSING TOWER

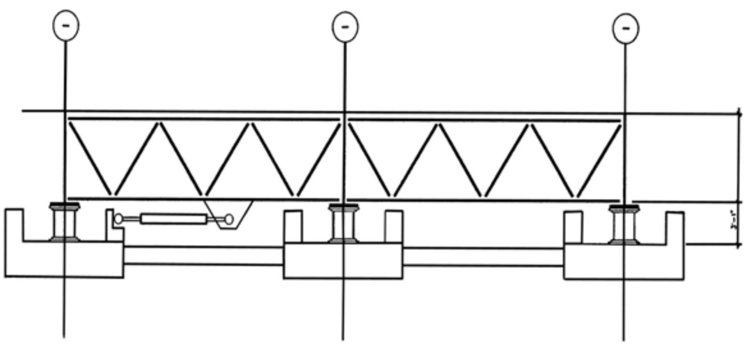


FIGURE 9
TYPICAL BUILDING – TRUSS TYPE 4 WITH DAMPERS

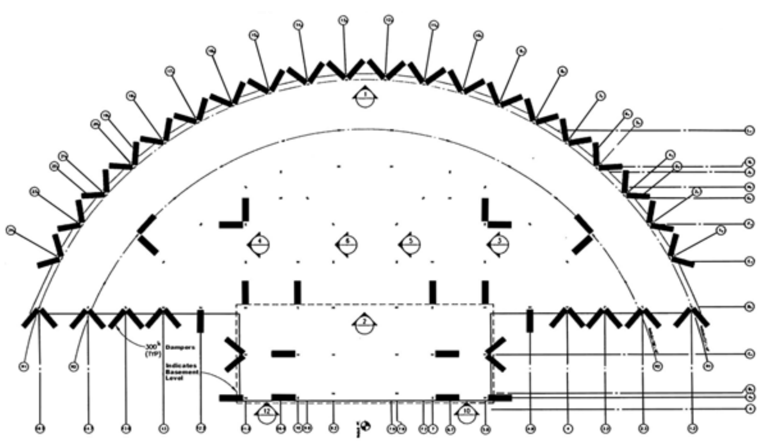


FIGURE 10
NURSING TOWER WITH DAMPERS

Analysis showed that expected worst case displacement of the structures on the elastomer pads alone was in excess of +/- 3 feet. This was far more than could be accommodated with any degree of economy. The addition of the dampers reduced this expected motion to a little under +/- 2 feet, which is acceptable.

Taylor Devices has produced test dampers which successfully met all evaluation criteria, and is now fabricating the production dampers.

Los Angeles City Hall

Fluid Viscous Dampers will be used in two places in the earthquake refurbishment of the Los Angeles City Hall, which is currently in process. Dampers in the sub-basement work in conjunction with elastomeric pad base isolation bearings. Dampers below the 27th floor are used without any other devices. They significantly reduce transverse motion of the heavy tower on top of the City Hall Building. This is an example of how it is possible to use fluid viscous dampers all by themselves to limit building deflection and structural forces, without having to use base isolators. This is done by utilizing the dampers as part of the structural bracing system.

CONCLUSIONS

The incorporation of viscous damping elements into any type of conventional base isolation system can often significantly improve performance, and also reduce overall cost of the structure.

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