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HISTORY, DESIGN, AND APPLICATIONS OF FLUID DAMPERS IN STRUCTURAL ENGINEERING

by

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ABSTRACT

The end of the Cold War in 1990 heralded a restructuring period for the American military and defense industry. One of the outcomes of this new era was that political and economic change allowed previously restricted technologies to become available to the general public. This conversion of U.S. defense technology is typified by highly advanced products and services that suddenly appeared in the marketplace, seemingly out of nowhere. Perhaps the best known of these is the now ubiquitous Internet, which in reality came from 1970's defense technology intended for use by government agencies in the event of nuclear war.

In the civil engineering field, high capacity fluid dampers have transitioned from defense related structures to commercial applications on buildings and bridges subjected to seismic and/or wind storm inputs. Because fluid damping technology was proven thoroughly reliable and robust through decades of Cold War usage, implementation on commercial structures has taken place very quickly.

This presentation is both an overview and a guide to implementation; with specific case studies being provided from four of more than 240 major buildings and bridges equipped with fluid dampers by Taylor Devices, Inc., a U.S. defense contractor from the Cold War years.

Keywords: Damper, damping, structural response, fluid, viscous

1. INTRODUCTION TO DAMPERS: DEFINITIONS AND FUNCTIONAL OUTPUT

The concept of damping within a structural system can have different meanings to the various engineering disciplines. To the civil engineer, damping may mean only a reference note on a seismic or wind spectral plot, "5% damped spectra" being the most common notation. To the structural engineer, damping means changes in overall stress within a structure subject to shock and vibration, with frequent arguments whether a structure will have "2%, 3%, 4%, but not more than 5%" structural damping. On the other hand, mechanical engineers do not necessarily view damping as a benevolent feature, since machines, by definition, are supposed to transmit forces and motions efficiently, without energy losses. Thus the need for damping in a machine often signifies that an engineering design error has been made.

In the classical mechanical engineering text "Vibration Theory and Applications," William Thomson [1] avoids a single, direct definition of damping by offering the following descriptions: "Vibrating systems are all more or less subject to *damping*, because energy is dissipated by friction and other resistances. Since no energy is supplied in free vibration, the motion in free vibration will diminish with time, and is said to be *damped.*"

It follows from these descriptions that a *damper* is an element which can be added to a system to provide forces which are resistive to motion, thus providing a means of energy dissipation. Assuming that this working definition will suffice for general use, the next area of interest is to generally describe the functional output of a damper. As with the definition of damping, the functional output of a damper is somewhat controversial, since different output equations exist within the context of the various engineering disciplines.

The most convenient and common functional output equation for a damper comes from classical systems theory, and is that of the so-called "*linear*" or "*viscous*" damping element:

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$$F = C\dot{X}^2$$

where F = resistive force from the damping element
C = the damping constant
$\dot{X}$ = end to end velocity across the element

It is rather unfortunate that the engineers who established systems theory probably began first with electrical systems, where the functional output of a resistor follows a simple and linear form. Using a damper as the mechanical analog to a resistor caused dampers to be described in the same, linear manner. In the days before computers, system problems had to be solved simply, due to the slow calculating speed of the slide rule. With a linear expression for damping, many differential equations could be solved by manipulation and cancellation of terms, allowing for an economic solution time.

Conversely, in mechanical engineering, it is difficult to manufacture a useable fluid filled component having a purely viscous output, because even moderate pressure hydraulic flows through a simple orifice follow a much different output equation, in which differential pressure varies with the fluid velocity squared. The resultant hydraulic component varies its output force with respect to the squares law, and is the so-called *hydraulic damping element*, or *dashpot*. The output of the basic hydraulic damping element is:

$$F = C\dot{X}$$

Decades ago, when engineers first began contemplating and analyzing systems with self-contained fluid dampers, the first problem to be solved was to develop a damper design that would provide an output more in keeping with systems theory than with the realities of simple hydraulic flows. Evidently the funding was going to the analysis team first, then trickling down to the design team. Because of the large amounts of research funding required, high performance damping products were eventually developed with defense budget funds, with public disclosure and use of the technology being restricted. The results of this research were several damper internal constructions that made it possible to achieve, or at least mimic, the desired linear output from systems theory. Eventually both analytical methods and damper designs evolved to provide more optimal solutions to shock and vibration problems, with dramatic advances occurring in the 1960's and 1970's. As a result, the most useful dampers being used today in buildings are of the so-called "*low exponent*" type, with an output equation of the form:

$$F = C\dot{X}^{\alpha}$$

In most cases, α is an exponent having a specified value in the range of 0.3 to 1.0. Values of α, which have proven to be most popular are in the range of 0.4 to 0.5 for building designs with seismic inputs. Bridge applications use similar damping exponent values. Bridge applications in low seismic zones often utilize an exponent of 2, that of the classical hydraulic damping element. Wind damping applications presently are most popular with exponents in the range of 0.5 to 1.0, with the lower values being used in structures driven by both wind and seismic inputs.

Other types of dampers exist which have very different outputs from viscous or fluid damping devices. These include so-called friction or hysteretic dampers, and rubber or visco-elastic dampers. A friction damper is essentially an on-off constant force device, where the resistive force to any motion, large or small, is a single fixed value. Rubber damping elements are relatively complex, and indeed no single output function exists to define the performance of rubber damping elements. The actual output varies with the type of rubber, how the rubber is shaped and constrained, and ambient temperature. In general, a rubber damping device can be modeled as a spring element in a series with a Voight element; the Voight element consisting of a spring and damper element in parallel with each other. In most cases, both hysteretic and rubber damping devices are only used where relatively small amounts of damping are required in a structure, usually less than 5% critical. The reasons for this will be discussed later on in this section.

1.1 Generalized Effects of Adding Damping to a Structure

Damping is one of many different methods that have been proposed for allowing a structure to achieve optimal performance when it is subjected to seismic, wind storm or other types of transient shock and vibration disturbances. Conventional approach would dictate that the structure must passively attenuate or dissipate the effects of transient inputs through a combination of strength, flexibility, deformability and energy absorption. The level of damping in a conventional structure is very low, and hence the amount of energy dissipated during transient disturbances is also very low. During strong motions, such as earthquakes, conventional structures usually deform well beyond their elastic limits, and remain intact only due to their ability to inelastically deform. Therefore, most of the energy dissipated is absorbed by the structure itself through localized damage.

The concept of added-on dampers within a structure assumes that some of the energy input to the structure from a transient will be absorbed, not by the structure itself, but rather by supplemental damping elements. An idealized supplemental damper would be of a form such that the force being produced by the damper is of such a magnitude and occurs at such a time that the damper forces do not increase overall stress in the structure. Properly implemented, an ideal damper should be able to simultaneously reduce both stress and deflection in the structure.

Figure 1 depicts earthquake spectra capacity and demand curves for a sample building with 20%, 30% and 40% damped demand curves. This Figure is reproduced from U.S. Government Publication FEMA 274 [2] and assumes linear or viscous damping elements are used.

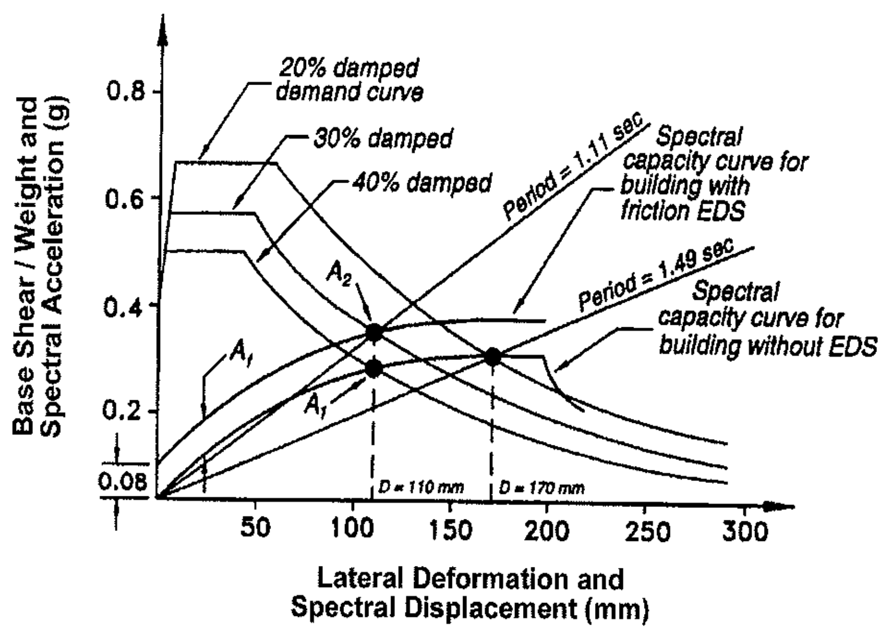


Figure 1. Spectral Capacity and Demand Curves for Rehabilitated One-Story Building

The effects of added supplemental damping in a structure subjected to earthquake transients is depicted in the test results provided in Figures 2 and 3. The tested structure was a single story, steel building frame, using steel moment frame connections. Figure 2 shows the response of the test structure under a scaled input of 33% of the 1940 El Centro earthquake. Note that a small hysteresis loop is apparent in Figure 2, revealing that the test structure was at the onset of yield. Structural damping in the frame was in the 1½-2% range. In comparison, Figure 3 is the same structure with 20% added damping, obtained by the addition of two small linear fluid dampers installed as diagonal brace elements. The large energy dissipation of added damping is readily apparent in the "football" shaped damping curve superimposed over the structural spring rate curve. Note also that the input in Figure 3 is the full 100% El Centro earthquake, yet base shear and deflection of the frame are virtually unchanged from the undamped case of Figure 2. Thus, in this case, the addition of 20% added linear damping to the structure increased its earthquake resistance by a factor of 3, compared to that of the same structure without added damping. Most importantly, this threefold performance improvement was obtained without increasing the stress or deflection in the structure. In fact, it is this tremendous performance improvement that caused much of the interest in fluid dampers for structural engineering use.

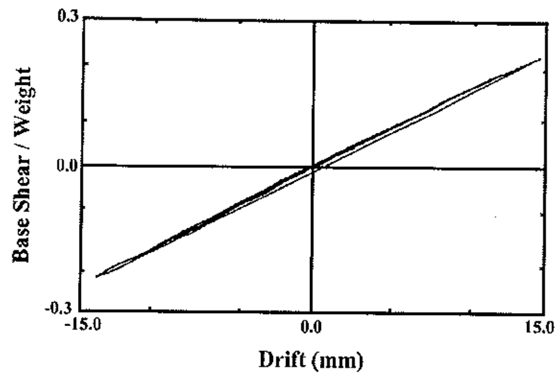


Figure 2. One-story Structure, No Dampers – El Centro 33.3%

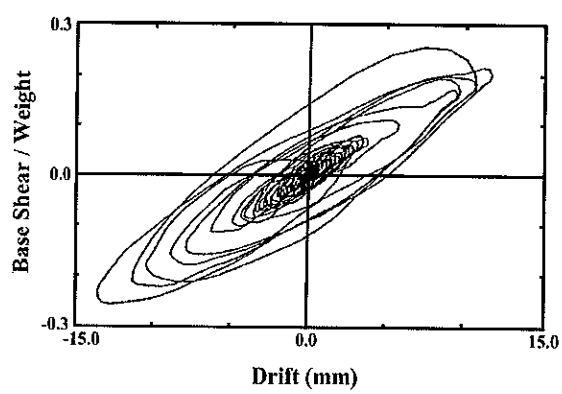


Figure 3. One-story Structure, Two Dampers – El Centro 100%

The test results from Figures 2 and 3 used the 1940 El Centro earthquake transient as a test input. When these results were first published in 1992 by Constantinou and Symans [3], they included tests showing similar performance gains with other notable earthquakes for which transient records were available. Nevertheless, questions have arisen in the ensuing years as to whether fluid dampers would be functional with other inputs, including actual earthquakes such as the 1994 Northridge, California and 1995 Kobe, Japan events, plus hypothetical inputs such as "a big, purely impulsive quake" or "a slow rolling sine wave quake." In addition, potential customers with wind storm inputs wanted to know if seismic dampers worked in wind, and Government customers wanted to know if damage from terrorist attacks against buildings would be reduced by dampers. The actual question being raised was simply: "Fluid dampers appear to be a useful engineering component. Are they truly useful for all types of shock and vibration inputs?" The answer is a definite yes, and it is relatively easy to demonstrate this by considering generalized qualities of a transient pulse.

The *first* and most important parameter of a transient is the peak translational velocity. The peak velocity is of primary importance because this determines the peak amount of energy that must be managed by the structural system. This velocity can be achieved by either a small acceleration over a long time period, or by a large acceleration over a short period. Thus, the maximum acceleration rate of the pulse is the *second* most important parameter of a transient, since the structure and the fluid dampers must be designed to accommodate the acceleration without being damaged by impulsive loadings. Figure 4 provides tabular data for maximum velocities and accelerations for catastrophic inputs. The least important parameters of the transient are those related to the actual shape of the various portions of the pulse. This is simply because no two discrete transients can be expected to be identical, these events being chaotic by their very nature. If one considers how a damped structure behaves under transients having a given maximum translational velocity and maximum acceleration then, in reality, only two simple extreme cases need to be considered.

Case One: The structure is excited by a step function, with acceleration equal to the maximum acceleration expected, for a time duration such that maximum translational velocity is obtained.

Case Two: The structure is excited by a forced sine wave at the frequency of the structure's first resonant mode, with input amplitude increased until the maximum specified acceleration or velocity is achieved.

An example of structural response to the first case, the impulsive input, is provided in Figure 5, for both the undamped and fluid damped condition. The response in this case assumed infinite acceleration, with velocity stepping from zero to maximum value instantaneously, and an elastic structure. It is readily apparent that the fluid damped structure experiences substantially less force and deflection than the undamped structure, even though each structure is storing or absorbing equal amounts of impulse energy.

An example of the second case is provided in Figure 6, from Thomson [1], and depicts the magnification factor on input amplitude for a system subjected to forced harmonic excitations with linear fluid damping. The condition of resonance is obtained at a frequency ratio of 1.0, and shows the tremendous benefits of fluid damping. The equation for magnification at resonance is:

$$\text{magnification factor} = \frac{1}{2\zeta}$$

where ζ = the damping ratio $\frac{C}{C_{cr}}$

Of particular note is that for a typical building with 2% damping, the magnification factor at resonance is 25 to 1. This number reduces to a much more manageable value of only 2 to 1 at 25% damping. It is of value to the engineer to note that virtually no structure is built with the safety factor of 25 to 1 necessary to accommodate the 2% damped resonant response. In comparison, most structures have sufficient safety factors to accept the 2 to 1 magnification for the 25% damped structure subjected to forced resonance.

From these examples, it is relatively easy to understand that fluid damping will always improve the response of a structure, under any expected transient.

TABULAR DATA FOR MAXIMUM VELOCITIES AND ACCELERATIONS		
	Peak Acceleration	Peak Velocity
Northridge Earthquake	.9 G	1.3 m/s
Kobe Earthquake	.8 G	.9 m/s
Ship, Moored Mine	25. G+	2.3 m/s+
Missile Silo, Nuclear Air Burst	80. G+	11.4 m/s+
Submarine, Nuclear Depth Charge	600. G+	12.7 m/s+

Figure 4. Catastrophic Transients

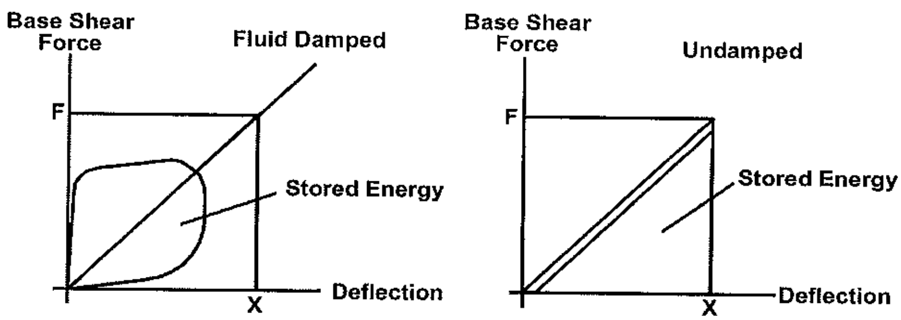


Figure 5. Response to Impulsive Inputs

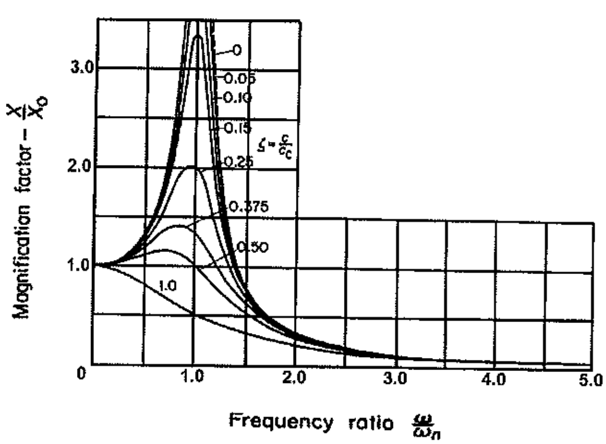


Figure 6. Magnification Factor for Forced Harmonic Excitation

1.2 Three Generic Types of Dampers and How Each of Them Affects a Structure

Fluid dampers have the unique ability to simultaneously reduce both stress and deflection within a structure subjected to a transient. This is because a fluid damper varies its force *only* with velocity, which provides a response that is inherently out-of-phase with stresses due to flexing of the structure. Other dampers can normally be classified as either hysteretic, where a fixed damping force is generated under any deflection, or as visco-elastic, where a damper behaves as a complex spring and damper combination. In the latter case, force may be a displacement *and* velocity dependent parameter. Figure 7 provides representative outputs from sine wave excitation of these three damper types. Inclusive in these non-fluid damper types are yielding elements, friction devices, plastic hinges, friction slides, bonded rubber, molded rubber, and shaped rubber. None of these other devices have an out-of-phase response to structural flexural stresses. This is simply because the outputs of these devices are dependent upon parameters other than, or in addition to, velocity. Hence, all of these other types of dampers will decrease deflection in a structure, but at the expense of increasing stress. The out-of-phase response that is unique to fluid dampers can be easily understood by considering a building shaking laterally back and forth during a seismic event or a windstorm.

Column stress is at a peak when the building has flexed a maximum amount from its normal position. This is also the point at which the flexed columns reverse direction to move back in the opposite direction. If we add a fluid damper to the building, damping force will reduce to zero at this point of maximum deflection. This is because the damper stroking velocity goes to zero as the columns reverse direction. As the building flexes back in the opposite direction, maximum damper force occurs at maximum velocity, which occurs when the column flexes through its normal, upright position. This is also the point where column stresses are at a minimum. It is this out-of-phase response that is the most desirable design aspect of fluid viscous damping.

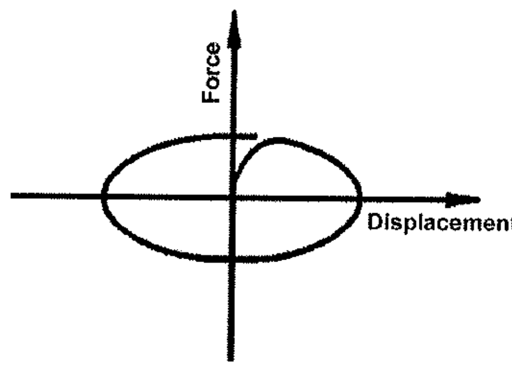
2. FLUID DAMPING DEVICES: A CENTURY OF HISTORY

It is axiomatic that during times of war, new technology develops extremely quickly, since the fates of nations may well depend upon which antagonist can mass-produce improved weapons more quickly. In the case of fluid dampers, the evolution of large bore artillery and naval guns in the late 1800's provided the need for the product, and the various major governments were eager to provide the development funding.

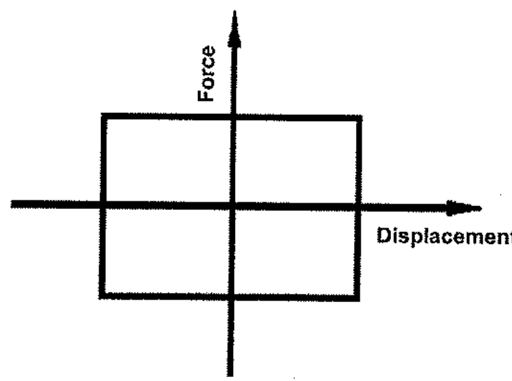
2.1 The Guns of War, 1897-1918 – Necessity Fosters Invention

The evolution of large dampers began with the advent of large breech loaded cannons in the 1860's. Prior to this, large guns were muzzle loaded in a very time-consuming manner. Gaining easy access to the gun's muzzle end for loading was simple, the weapon was merely allowed to move backwards anywhere from 0.3 m to 7m after firing. Motion was retarded by means of a shovel-like device literally digging into the earth on land-based weapons. Shipboard guns used friction slides or inclined surfaces to arrest their firing motion, often aided with block and tackle mechanisms. After loading, the gun crew would push the gun back into its ready-to-fire position. The advent of breech loading allowed for much more rapid (and safer) loading of the weapon, and a desirable higher rate of fire. Unfortunately, the high firing rate required that the gun crew work much faster to reposition the gun, quickly tiring the crew.

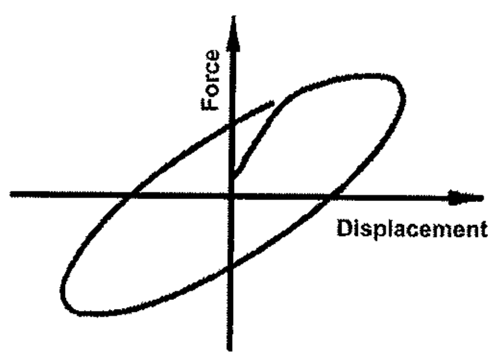
Several unsuccessful concepts of arresting gun recoil were attempted, involving both coil springs and rubber blocks. Meanwhile, the inventors of that time were investigating the new field of hydraulic components, and by the late 1860's, experiments were taking place using hydraulic dampers to arrest gun recoil. It is reported by Hogg [4] that the British Army was the first to use hydraulic recoil dampers on gun carriages, in 1862. The first mass-produced hydraulic recoil damper was used on the 75 mm French field gun, Model M1897. This weapon was hailed as a true technological marvel and is considered to be the first modern artillery piece. The carriage of the weapon included a slide to support the gun itself, and a 1.2 m stroke fluid damper combined with a light spring to attenuate recoil energy and return the gun to battery. The French M1897 went on to serve in both World War I and World War II. One of the more unusual uses for the low recoil French M1897 was by the U.S. Army Air Corps during World War II. The Air Corps needed a ground attack aircraft with as much firepower as possible. The solution to the problem involved mounting a complete M1897 gun with recoil dampers into the nose of the U.S. Model B-25 "Mitchell" Bomber, firing forward. The modified aircraft proved successful, and the use of the hydraulic dampers eliminated damage to the aircraft.



Fluid Viscous Output



Friction Output



Viscoelastic Output

Figure 7. Output of the Three Generic Damper Types

By the end of World War I, tens of thousands of fluid dampers were being used on field artillery pieces, naval guns, coastal guns and railway guns. Some dampers of this period were even of the semi-active type, where changing the gun elevation angle would change the resultant damping force. This was accomplished by using a gear train between gun carriage and the damper. The gear train would rotate an adjustment rod or screw protruding from the damper cylinder. As the gun was elevated, the damper would become stiffer, and use less displacement. This feature allowed the gun carriage to be reduced in size and weight, since at high elevation angles, the carriage no longer needed to maintain clearance to the ground for the entire recoil stroke.

Toward the end of World War I, another advantage of fluid dampers was discovered. This was that reduced recoil allowed weapons to easily fire larger projectiles, with larger propellant charges to obtain greater range. Indeed, from March to July of 1918, the City of Paris was attacked by the German Army with a weapon of "super gun" proportions. Details did not become available until the war ended, and then only after intense efforts by the allies. The weapon was named the Paris Gun, and included a 40 m long barrel, which fired a 210 mm diameter shell at a range up to 135 km. The gun itself, with fluid dampers, weighed over 120 tonnes, not including the weight of the tremendous carriage that carried the weapon. Three of the Paris Guns were built, but all were withdrawn from service as the allied armies approached their locations.

2.2 The Automotive Damper – Optimization Through Evolution

The 1920's and 1930's were a period when the automobile became a dominant feature of American culture. Since the automobile was a relatively new product with a large potential market, automotive manufacturers were forced, by competitive pressures, to produce a product that would be appealing to the consumer. One of the most appealing traits that an automobile could possess was a smooth ride over all possible road surfaces; this proved to be a true challenge for automotive engineers of this period.

The earliest auto suspensions were simply carried over from horse-drawn wagons. The suspension consisted of multiple leaf elliptical or semi-elliptical springs. Damping was limited to the inter-leaf friction which occurred as the spring leaves ground over one another as the spring deflected. Damping would obviously have a high variance from day-to-day, depending on whether the spring was dry, wet, rusty, dirty, or recently cleaned and oiled.

This day-to-day damping change proved unacceptable to the consumer, and external friction pad or rubber dampers were added to the suspension. These provided a small but noticeable improvement over using the spring itself as a damper, plus it was possible to make the damper adjustable for wear. The "ideal" damping material was usually *pure asbestos* washers or pads, compressed between two iron plates. One plate was fixed to the car frame by a bolt, the other was attached to an actuating arm. A large draw bolt went through the center of the damper assembly, and tightening or loosening of the bolt served to adjust the damping force.

The high maintenance and marginal improvement obtained with friction and rubber dampers caused automotive parts suppliers to look for improved damping systems, and fluid dampers quickly entered the scene. The biggest problem with adapting the fluid damper for automotive use proved to be poor quality seals. The guns of World War I usually needed a major overhaul every 500 rounds due to barrel wear, and this was an opportune time to change damper seals, which usually were leaking badly after 500 cycles. Considering that the seals of the day consisted of cut lengths of hemp rope forced into a pocket, this was no surprise! "Improved" seals of the 1920's consisted of a stack of round leather washers forced into position with a packing nut. These were an improvement over hemp strands, but still could not provide the cyclic life necessary for automotive use.

In 1925, Ralph Peo of the Houdaille Company in Buffalo, New York, U.S.A. invented a solution to the seal problem. Instead of improving the seal, he redesigned the damper to use a rotating piston rod and vane assembly, thus replacing long travel, sliding seal motion with a short 60-120 degree rotary travel. The Houdaille rotary damper was actuated by crank arms attached to the moving components of the suspension. The short rotary travel of the seal allowed for roughly 16,000 km of road travel before seal replacement was necessary. Within a short period, most automobiles were using the Houdaille rotary damper. Figure 8 is one of the original patent sheets depicting Peo's 1925 invention.

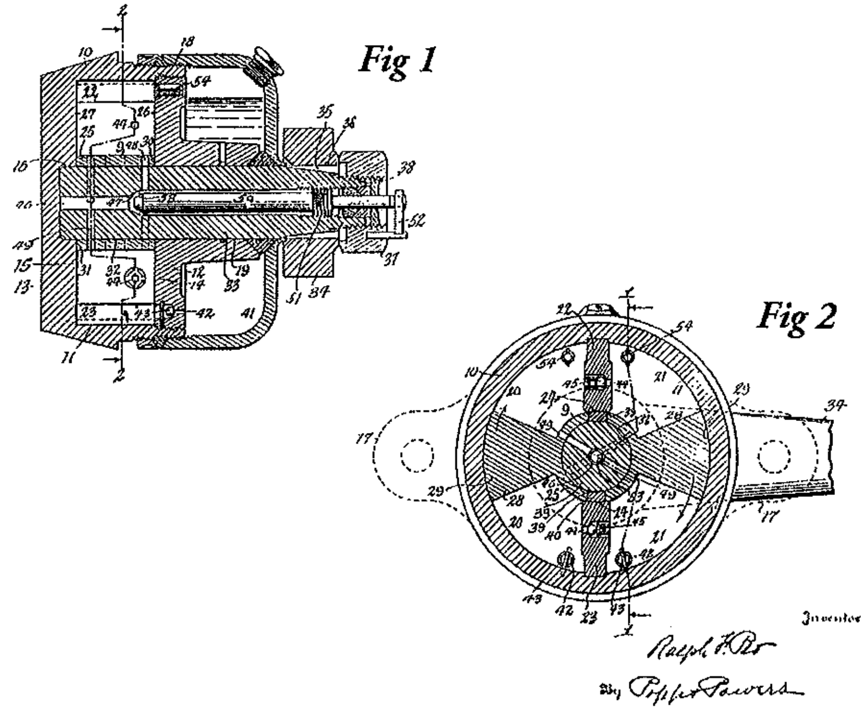


Figure 8. Patent Sheet – R. Peo's Rotary Shock Absorber

In 1949, the Delco Division of General Motors finally designed a sliding seal damper that had an adequate life for automotive use, thus ending the rotary damper era. Present-day automotive shock absorbers have an internal construction that is very similar to the gun recoil buffers of World War I, except that modern seals provide substantially greater life.

2.3 The Cold War – Dampers Go Underground

History texts will eventually include great amounts of information about the Cold War period, which lasted from the end of World War II to approximately 1990. Detailed information will be presented only as it is declassified, and this will take many years. Early on in the Cold War, both the United States and Russia began developing intercontinental ballistic missiles (ICBM), equipped with nuclear warheads. Although still debated, most defense analysts state that the U.S. strategic war doctrine was such that our missiles would not be launched until enemy warheads had actually detonated on or above U.S. soil. Adherence to this doctrine assumed that the enemy's initial targets would be U.S. missile launchers, striking as many of these as possible in a first strike. In order for the U.S. to launch a counterstrike under these conditions, our missiles needed to be designed and/or based in such a way that they could survive a nuclear attack without damage. Initially, land based missiles were simply placed underground in heavily reinforced launch silos, usually accompanied by underground launch facility buildings. However, as missile guidance systems evolved, the accuracy of enemy missiles was improved, and the need for shock isolation devices became apparent. Early missile isolators consisted of simple coil springs with fluid dampers. In some cases, the spring-damper units were used to isolate the missiles themselves and various critical items inside the launch complex. In other cases, entire structures were base isolated in both vertical and horizontal planes, using coil springs and fluid dampers.

During the 1960's, it became impossible to provide large enough mechanical springs to provide the optimal isolation, so fluid dampers were converted to liquid-spring dampers, an extremely powerful yet compact isolation component. In a liquid spring-damper, the operating fluid is compressed and orificed simultaneously. Thus, a single element provides both spring and damping forces. By selecting special fluids with high compressibility, it was possible to produce both high spring and damping forces in an extremely small package. Some of the liquid spring-dampers of the late 1980's could simultaneously provide spring forces of 50 tonnes and damping forces of 150 tonnes from a package of only 180 mm in diameter! Operating fluid pressures of up to 345,000 kPa were relatively common. In comparison, a high-powered hunting rifle has peak firing pressures in the 270,000 kPa range. Some of the these products for large land based missiles had more than 1.5 m of displacement, with output forces up to 500 tonnes.

The successful use of high capacity fluid dampers and liquid spring-dampers on land based missile facilities led to additional applications on shipboard and submarine missiles and related equipment items. By the end of the Cold War, a typical U.S. Naval warship would have more than 1,000 fluid damping devices installed on its missiles and primary electronics systems. These devices range from 1 tonne to 50 tonnes of output force.

During the 1990's, the end of the Cold War combined with the political and economic climate caused a dramatic downsizing of U.S. defense capabilities. At the same time, security restrictions on the sale and commercial use of Cold War era technology had been greatly relaxed.

2.4 The Last Ten Years – Transition of Defense Technology to the Private Sector

Both U.S. and Soviet Bloc Defense firms found very few new opportunities in their traditional markets when the Cold War ended. Some firms grew smaller, or maintained sales levels by oftentimes painful mergers or consolidations. Relatively few firms were able to transition their technology to the commercial marketplace. Taylor Devices, Inc., a New York based manufacturer of energy absorption products for military and defense use, began to look for commercial outlets for its defense products in 1987.

Taylor Devices' defense expertise involved the design and manufacture of large, fluid damping devices for protection of missiles, electronics systems, and large structures against the effects of weapons explosion. The company elected to pursue commercial applications related to seismic and high wind protection of structures. The damper style selected dated from the 1970's, and was developed on a sole-source basis by the firm for use on the U.S. Air Force's MX Ballistic Missile, and the U.S. Navy's Tomahawk Cruise Missile. On the latter program, the company has produced more than 29,000 fluid damping devices.

Early on, it was decided to pursue joint research on fluid damped building and bridge structures with the National Center for Earthquake Engineering Research (NCEER). NCEER was located on the campus of the State University of New York at Buffalo, just a short distance from Taylor Devices' facilities. The research involved taking existing military production fluid damping devices, and simply installing them onto scaled models of civil engineering structures, as supplemental components. The structures were then subjected to seismic transient testing on the University's large seismic shake table. All tests proved excellent, with dramatic reductions of stress and deflection occurring with added fluid damping in the 15-40% range.

In general, it was found that adding 20% damping to a structure will triple its earthquake resistance, without increasing stress or deflection. Numerous reports were published by NCEER and the University, documenting the improvements obtainable with fluid dampers. The U.S. Department of Defense proved very cooperative in allowing Taylor Devices to disclose the origins and applicable design concepts for the damping devices used in the research.

For example, steel building structures were tested with fluid dampers produced for the B-2 Stealth Bomber. Concrete building structures were tested using Tomahawk missile dampers. Bridge structures were tested with dampers from the CIA's famed Glomar Explorer Research Vessel. Other bridge structures were fitted with spring-damper units from submarine based torpedoes.

It became evident that there were no barriers towards commercial implementation of Taylor's damping products, and by 1993, an order was received for 186 dampers to be used on all five buildings of the new Arrowhead Regional Medical Center in Colton, California. Specifications for these dampers are provided in Figure 9, and a photo of a completed damper follows in Figure 10.

DAMPER SPECIFICATIONS SAN BERNARDINO COUNTY MEDICAL CENTER		
Displacement	=	**1.2 m**
Max Damping Force	=	**145 tonnes**
Max Operating Velocity	=	**1.6 m/s**
Power Dissipation	=	**2,170,000 watts**
Length	=	**4.5 m extended**
Diameter	=	**0.36 m**
Weight	=	**1360 kg**
Quantity Required	=	**186 units**

Figure 9. San Bernardino County Medical Center Damper Specifications

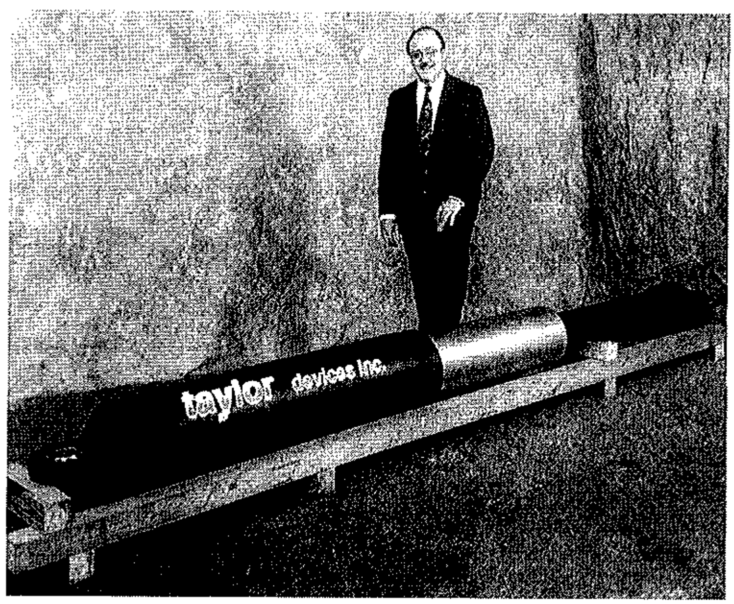


Figure 10. Photograph of Completed Damper

No design or development was necessary by Taylor Devices to build these large dampers, even though each device produces 145 tonnes of force and has a 1.2 m displacement. The reason was simply that it already was a production design, used as the vertical shock isolator for the U.S. Air Force MX Ballistic Missile, dating to 1978.

More than 240 additional building and bridge projects followed the Arrowhead Medical Center order.

3. FLUID DAMPERS FOR BUILDING AND BRIDGE STRUCTURES

The design elements of a fluid damper are relatively few. However, the detailing of these elements varies greatly and can, in some cases, become both difficult and complex. Figure 11 depicts a typical fluid damper and its parts. It can be seen that by simply moving the piston rod back and forth, fluid is orificed through the piston head orifices, generating damping force.

Major part descriptions are as follows, using Figure 11 as reference:

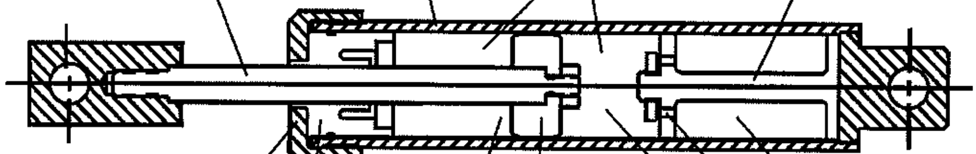


Figure 11. Fluid Damper

Piston Rod – Highly polished on its outside diameter, the piston rod slides through the seal and seal retainer. The external end of the piston rod is affixed to one of the two mounting clevises. The internal end of the piston rod attaches to the piston head. In general, the piston rod must react all damping forces, plus provide a sealing interface with the seal. Since the piston rod is relatively slender and must support column loading conditions, it is normally manufactured from high-strength steel material. Stainless steel is preferred as a piston rod material, since any type of rust or corrosion on the rod surface can cause catastrophic seal failure. In some cases, the stainless steel must be chrome plated for compatibility with the seal material. In addition, the design of the piston rod should be strain based, rather than stress based, since elastic flexing of the piston rod during damper compression can cause binding or seal leakage. Bending loads on the piston rod can become a design issue if a damper has more than 0.3 m of displacement. For applications requiring a long stroke, a structural steel tube guide sleeve is used to protect the piston rod from excessive bending loads. The Arrowhead Medical Center damper, shown previously in Figure 10, incorporates a guide sleeve of this type.

Cylinder – The damper cylinder contains the fluid medium and must accept pressure vessel loading when the damper is operating. Cylinders are usually manufactured from seamless steel tubing. Welded or cast construction is not permissible for damper cylinders, due to concerns about fatigue life and stress cracking.

Cylinders normally are designed for a minimum proof pressure loading equal to 1.5 times the internal pressure expected under a maximum credible seismic event. By definition, the proof pressure loading must be accommodated by the cylinder without yielding, damage, or leakage of any type.

Fluid – Dampers used in structural engineering applications require a fluid that is fire-resistant, non-toxic, thermally stable, and which will not degrade with age. This fluid must be classified as both non-flammable and non-combustible, with a fluid flashpoint above 90°C. At present, the only fluids possessing all of these attributes are from the silicone family. Typical silicone fluids have a flashpoint in excess of 340°C, are cosmetically inert, completely non-toxic, and are thermally stable. Since silicone fluids are produced by distillation, the fluid is completely uniform and no long-term settling will occur. The typical silicone fluid used in a damper is virtually identical to the silicone used in common hand and facial cream cosmetics.

Seal – The seals used in a fluid damper must be capable of a long service life; at least 25 years without requiring periodic replacement. The seal materials must be carefully chosen for this service life requirement and for compatibility with the damper's fluid. Since dampers in structures are often subject to long periods of infrequent use, seals must not exhibit long-term sticking nor allow slow seepage of fluid. Most dampers use dynamic seals at the piston rod interface, and static seals where the end caps or seal retainers are attached to the cylinder. For static seals, conventional elastomer o-ring seals have proven to be acceptable. Dynamic seals for the piston rod should be manufactured from high-strength structural polymers, to eliminate sticking or compression set during long periods of inactivity. Typical dynamic seal materials include Teflon®, stabilized nylon, and members of the acetyl resin family. Dynamic seals manufactured from structural polymers do not age, degrade, or cold flow over time. In comparison, conventional elastomers will require periodic replacement if used as dynamic seals in a damper.

Piston Head – The piston head attaches to the piston rod, and effectively divides the cylinder into two pressure chambers. As such, the piston head serves to sweep fluid through orifices located inside it, thus generating damping pressure. The piston head is usually a very close fit to the cylinder bore; in some cases the piston head may even incorporate a seal to the cylinder bore.

Seal Retainer – Used to close open ends of the cylinder, these are often referred to as end caps, end plates, or stuffing boxes. It is preferable to use large diameter threads turned on either the exterior or interior surface of the cylinder to engage the seal retainer. Alternate attachment means, such as multiple bolts, studs, or cylinder tie rods should be avoided as these can be excited to resonance by high frequency portions of either the earthquake transient or the building response spectra. Tie rods should not be used since they generally constitute an unacceptable single point failure; a catastrophic design flaw. If even a single tie rod yields during a seismic event, the seal retainer will usually bend or rotate such that an open gap appears between the cylinder and retainer. The damping fluid is literally pumped out of the damper through this open gap. This problem does not occur with a seal retainer that is threaded directly into the cylinder bore. In this case, if a single thread yields, the pressure loading is distributed among the numerous remaining threads.

Accumulator – The simple damper depicted in Figure 11 utilizes an internal, in-line rod make-up accumulator. The accumulator consists of either a block of closed cell plastic foam, a moveable (and gas pressurized) accumulator piston, or a rubber bladder. The purpose of the accumulator is to allow for the volumetric displacement of the piston rod as it enters or exits the damper during excitation. A second purpose is to compensate for thermal expansion and contraction of the fluid. The damper in Figure 11 uses a control valve to meter the amount of fluid displaced into the accumulator when the damper is being compressed. When the damper extends, the control valve opens to allow fluid from the accumulator to freely enter the damper pressure chambers. Although the damper in Figure 11 has an in-line, internal accumulator, some older damper types use an external accumulator tank with connecting hoses or piping.

Orifices – The pressurized flow of the fluid across the piston head is controlled by orifices. These can consist of a complex modular machined passageways, or alternately, can use drilled holes, spring loaded balls, poppets, or spools. Relatively complex orifices are needed if the damper is to produce output with a damping exponent of less than two. Indeed, a simple drilled hole orifice will follow Bernoulli's equation, and damper output will be limited to varying force with the square of the damper velocity. Since "velocity squared" damping is of limited use in seismic energy dissipation, more robust and sophisticated orifice methods are usually required.

4. IMPLEMENTATION OF FLUID DAMPERS

One of the most beneficial aspects of using fluid dampers in a structure is that they are essentially a "bolt-in" item, of a relatively compact size. If used as part of a structural bracing system, the fluid dampers usually will have a smaller cross-sectional envelope than a conventional steel brace.

4.1 Fabrication Issues: Size vs. Cost

If a given structure requires certain total macroscopic damping, to implement this damping will involve dividing the total damping by the number of dampers used. The end result is a maximum force and damping function for each individual damper. The question is: Should the engineer select a large number of small dampers, or a lesser number of large dampers? The rather large number of available dampers sizes tends to compound the problem even further.

The structural engineer normally starts out with multiple dampers of the same size, dispersed uniformly throughout the structure. This usually results in many dampers in the relatively small force range of 5 tonnes to 25 tonnes output. If the structure is small enough to require less than 32 pieces of a 5 tonnes to 25 tonnes output damper, than this will probably be the most effective size, since quantities smaller than 32 pieces tend to become costly, due to set-up, engineering, and test charges being amortized over a small quantity. The 32 piece number was obtained strictly from the past experience of the author.

The next step is to reduce the number of dampers by using the next larger size, and continuing this process until:

1. The quantity of dampers goes below 32 pieces.
2. The force rating of the damper goes over 300 tonnes.
3. The structure begins behaving less efficiently because the dampers are not distributed well enough.

This is an interactive process, and thus damper sizes will vary from project to project.

Currently available damper sizes from manufacturers range from 5-800 tonnes of force output. In terms of relative cost, the least expensive sizes on a force basis are usually in the 100-250 tonnes range, i.e., one piece of a 150 tonnes force damper costs less than 10 pieces of a 15 tonnes force damper. In most cases, dampers larger than 600 tonnes output are used only on large bridges, since the point loading into a building structure from such a large device requires that special design considerations be made to the structure's beam to column connections. Also, note that just as 15 tonnes force dampers are relatively expensive compared to the 150 tonnes size, dampers larger than 250 tonnes also tend to become costly. In this case, the problem relates to a general lack of available high-strength steel in the very large sizes, requiring special orders to the steel mill.

4.2 Tuned Mass Fluid Dampers for Tall Buildings

A special design case for fluid dampers occurs when they are selected for use as part of a tuned mass damper system for tall buildings. This application suspends a large internal lumped mass at the uppermost floors of a tall building, supporting the mass with cables, steel arms, or springs combined with air/fluid/mechanical slider bearings. The end result is to have the mass centered within the building on lateral spring elements. The dampers, which typically have strokes in the 0.6-2 m range, are used to control the response of the tuned mass and springs. When the building is subjected to wind inputs, the building will tend to move with the wind. The tuned mass, due to its inertia and long period attachment, prefers not to move. Thus, the tuned mass reduces deflection of the building under wind inputs by essentially applying force to the building in a direction resistive to the wind motion. Tuned masses are not normally used to provide seismic protection, since they can be ineffective and even dangerous under the high energy and unpredictability of a seismic event.

The biggest problem encountered with tuned mass dampers is that they must stroke long distances, almost continually, for the life of the building. This naturally brings up the issue of seal wear, which in itself is compounded by the tuned mass damper requiring very low seal friction to allow the mass to move freely. The end result is that a conventional damper modified with low tension seals and used in a tuned mass system will require that seals be replaced every 1-2 years. In comparison, dampers for use with base isolation or distributed damping elements within a building do not normally deflect long distances under wind motion. Seals in these dampers can be expected to last 10-35 years.

4.3 Linkage Driven Dampers for Stiff Structural Systems

Structures that are inherently stiff or rigid often require that fluid dampers function with extremely small displacements, down to plus or minus 2 mm or less. Unfortunately, when a damper is operated with small displacements, relatively small damping pressures are generated. This is because all fluids are slightly compressible, and the cylinder of the damper expands slightly under pressure.

Two solutions are presently available to address this problem. One is simply to use a very large damper with heavy cylinder walls, operating at very low pressures. This solution is often costly, and dampers operating at very low pressures are subject to viscous effects, changing their output force radically as the ambient temperature varies the viscosity of the damping fluid.

The second solution is more practical, and comes from the field of mechanical engineering. This solution involves the use of a lever driven mechanism to multiply the deflection of the structure. Figure 12 depicts such a mechanism, called a toggle brace element. Shake table tests on this mechanism by Taylor and Constantinou [5] revealed that it was possible to obtain a 3:1 increase in the measured story drift at the mounting points of the damper. Overall performance of the tested system was virtually identical to that obtainable with a larger and much more costly direct acting damper, without encountering the viscous effects problem.

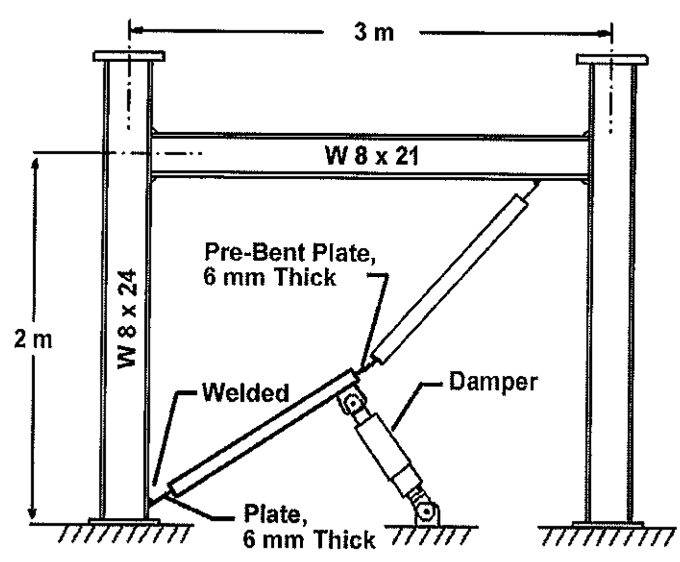


Figure 12. Tested Frame with Toggle Brace-Damper System

4.4 Detailing Issues: Attachments and Brace Styles

There are three basic ways to attach dampers into a building or bridge structure.

1. Base isolation dampers have clevises and spherical bearings at each end. These long stroke dampers are connected to the foundation and to the building frame respectively, using mounting pins. Note that the mounting pins for base isolation dampers *must* be oriented vertically, to allow proper articulation during out of plane motion.

2. Dampers for chevron bracing systems have clevises and spherical bearings at each end. Connections are similar to base isolation dampers, except that the mounting pins are usually oriented horizontally. The typical plus or minus 5° rotation angle of a spherical bearing will accommodate out of plane motion for the relatively small drifts encountered with this type of installation.

3. Dampers for diagonal bracing systems have a clevis with spherical bearing at one end, and a mounting plate at the opposite end. The mounting plate attaches to a brace extender.

Schematics of the three basic mounting attachment styles are provided in Figure 13. The mounting pins used to attach the dampers to brackets or tangs are often supplied by the damper manufacturer. In most cases, the manufacturer will also provide the brackets or tangs used to connect to the building structure. The reason for this is that the pins must be fitted very closely to the clevises and spherical bearings, to insure that the connection has no discernable play. The pins themselves are normally fabricated from high strength stainless steel. Each mounting pin extends entirely through clevises and tangs, and includes cross drilled holes at each end. Large cotter keys are inserted into the cross drilled holes to finish the installation. Figure 14 depicts a spherical bearing and Figure 15 is a schematic of a completed attachment.

The spherical bearings are installed into the damper clevis by the manufacturer. Depending on the structure, the bearings themselves can be plated steel, coated steel, or stainless steel. For bridge applications, seals are added to stainless steel or plated steel bearings to reduce potential for corrosion.

There is a certain degree of variance in the design of diagonal brace elements. In many cases, the building's out of plane motion is small enough that a long extender brace can simply be welded to the beam to column connections, with the opposite end of the extender attached to the damper. Thus, the damper's single clevis and bearing is the only connection capable of articulation. If the brace and damper elements are relatively short, then clevises must be used at each end of the damper-brace combination.

4.5 Maintenance and Inspection

Maintenance is not required for a properly designed and manufactured fluid damper used for seismic and wind damping in structures. Usually, visual inspection of the dampers should occur after a major seismic or wind storm event. In general, visual inspection involves looking for discernable leakage or broken parts and/or connections. In the event of seismic overload, the damper mounting pins may bend or shear. Pin condition can be ascertained by simply rotating the pin, checking to see if the damper clevis "wobbles" as the pin is turned.

After a major seismic event, some structures may require an enhanced inspection, due to regional code requirements. This may involve as little as verifying that the damper is full of fluid. In some cases, regulations may require that a few dampers be removed at random from the structure, and subject to testing to verify damping output. In all cases, any site personnel who will be involved in repairing dampers or replacing damper parts must be employees of the damper manufacturer. This is necessary for insurance and product liability considerations.

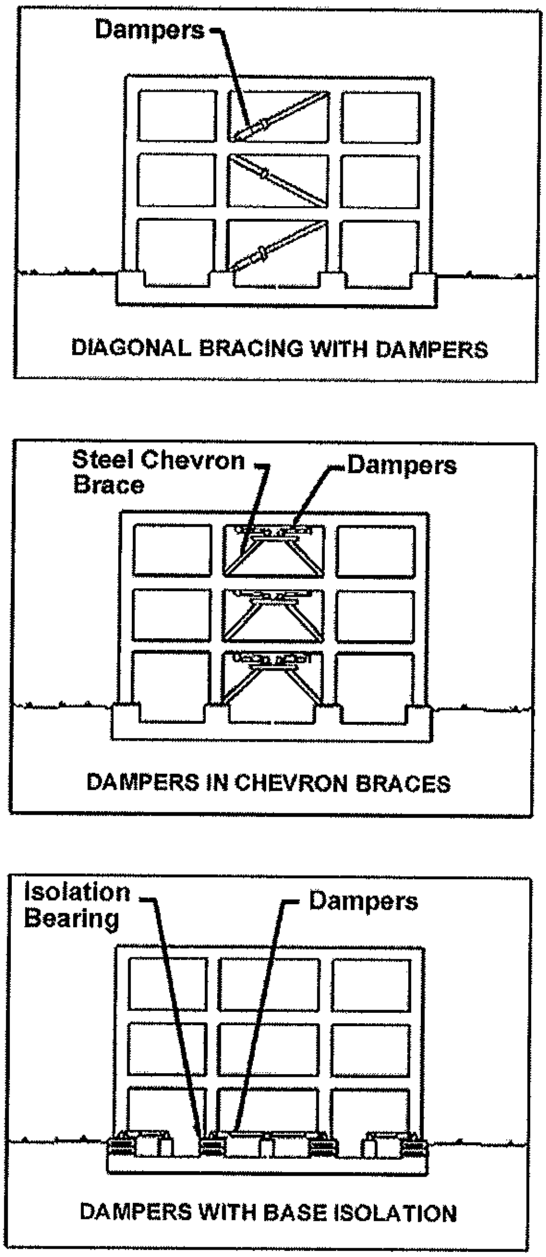


Figure 13. Basic Mounting Attachment Styles

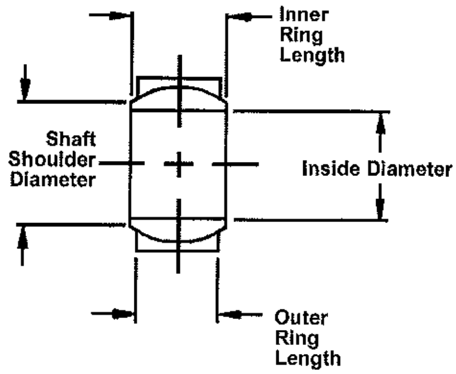


Figure 14. Spherical Bearing

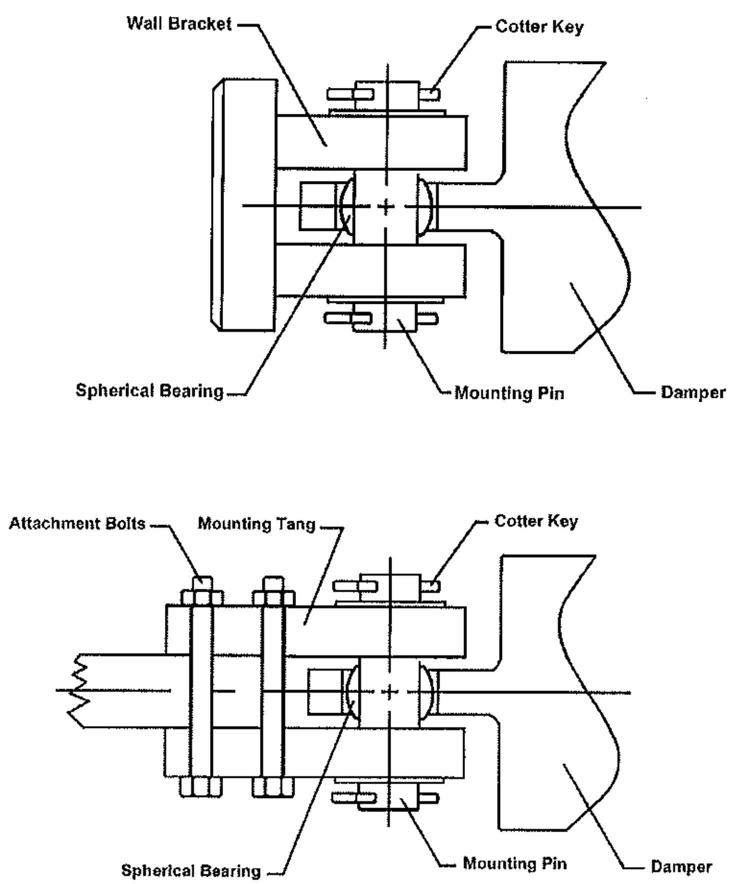


Figure 15. Schematic of a Completed Attachment

5. PROJECT EXAMPLES

At this time, more than 240 major structures are using fluid dampers to obtain enhanced performance during seismic or wind excitation. Four of these projects are described here.

5.1 Los Angeles City Hall

This large 32-story Government office building was built in 1926, and even today is still the central focal point of downtown Los Angeles, California.

The construction of the building used what was considered the most advanced method of seismic protection for the 1920's – a steel frame with massive concrete shear walls. It was the first structure to exceed an earlier code height limitation of 46 m in the City of Los Angeles. Until the late 1950's, it was the tallest building in Los Angeles. The structure measures 144 m long, is 82 m wide, and rises to a height of 140 m. Total floor area is 85,000 square meters.

Since the building was first constructed, the Los Angeles area has experienced numerous earthquakes, many of which caused extensive damage to the structure. After major earthquakes in 1971, 1987, and 1994, especially heavy damage was noted in the higher floors, with large cracks occurring in masonry infill and the concrete walls. After the 1994 Northridge earthquake, a decision was made to seismically upgrade the facility, using base isolation.

The seismic retrofit required a total of 416 rubber base isolation bearings. Due to the high shaking speed of the Northridge earthquake, peak design translational velocity for the isolation system was very high; fixed at 2 meters per second. A total of 52 fluid dampers were installed in parallel with the isolation bearings to dissipate seismic energy and reduce the required bearing displacement. Each damper produces 180 tonnes output force, and has an available displacement of plus or minus 0.65 m. Low exponent damping in the $V^{.5}$ range was selected for the base isolation dampers. These dampers also served to reduce amplification of seismic loads in the tower structure.

In order to reduce tower loadings even further at floors 24 through 32, an additional 14 fluid dampers of 135 tonnes force and plus or minus 115 mm stoke were installed in chevron bracing elements. These dampers are installed on the 27th floor.

The Los Angeles City Hall was reopened in 2001, after the seismic retrofit was completed.

Figures 16-17 show the application and the dampers

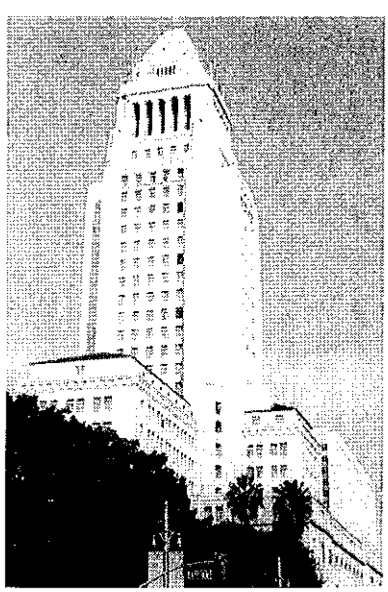


Figure 16. Los Angeles City Hall

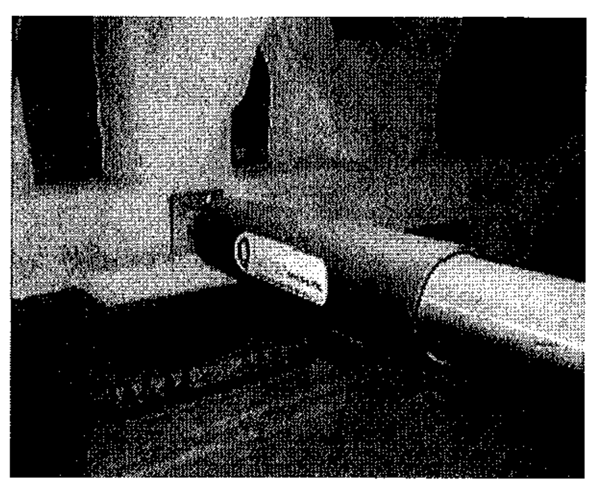


Figure 17. Los Angeles Installation of Damper

5.2 The San Francisco Civic Center Office Building

Those who are familiar with seismic designs in San Francisco will agree that this historic city is literally the "home of the braced steel seismic resistant frame." When the 1994 Northridge, California earthquake revealed problems with steel moment frames, one would normally anticipate the desire for braced frames to become even stronger. One can then imagine the surprise within the structural engineering community during 1996, when erection began on the 14-story San Francisco Civic Center office building. This 75,000 square meter structure combined 292 fluid dampers with the so-called "post-Northridge" moment frame to optimize performance while maintaining a cost-effective project budget. Two different damper force levels were used by the engineer, 100 tonnes and 55 tonnes. All dampers were plus or minus 100 mm stroke. The dampers were used in diagonal brace elements, with a bolted flange connection to attach dampers to their brace extenders. The piston rod end of the damper incorporated a clevis with spherical bearing, as did the opposite end of the brace extenders. The dampers were supplied with building attachment clevises, which consisted of simple tang plates that were bolted to a gusset plate at the building's beam to column connections. Low exponent damping in the $V^{.4}$ range was selected, combined with a building frame that can provide extensive inelastic deformation. The use of low exponent damping tended to limit damper forces when the frame was loaded into the inelastic range.

Figures 18-20 show the application and the dampers

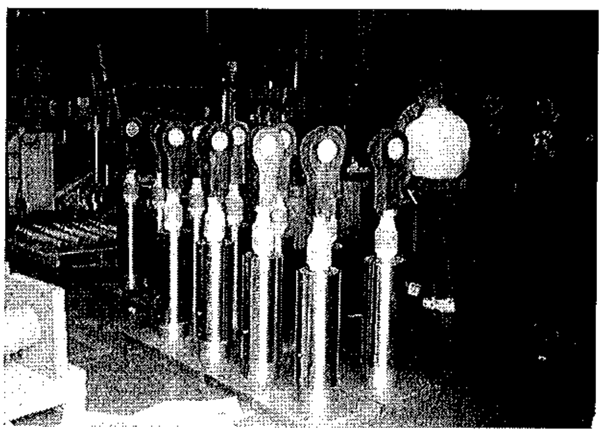


Figure 18. San Francisco Civic Center Dampers Readied for Final Painting

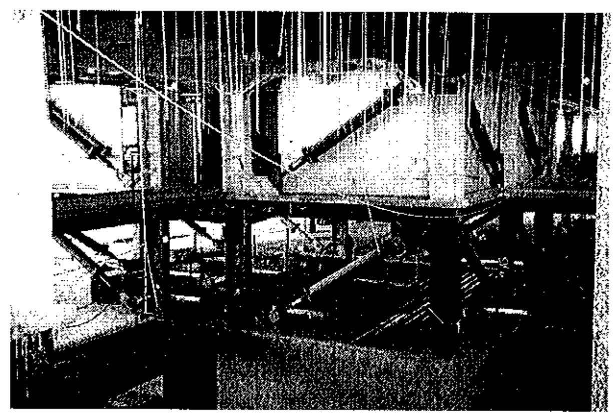


Figure 19. San Francisco Civic Center Damper Installation

Figure 20. San Francisco Civic Center Damper Closeup Showing Connection Details

5.3 Torre Mayor at Mexico City, Mexico

The new fifty-five floor Torre Mayor office building is the dominant building in the Mexico City skyline, and the tallest building in Mexico. Located in the Reforma Centro business district, the 78,000 square meter structure is sited in an area leveled by the 1985 Mexico City earthquake.

The design approach used by the engineering team used fluid dampers to reduce seismic stress below code requirements, and then reduce the amount of steel required in the building frame until structural stress increased to allowable code values. This allowed a fifty-five floor building to be constructed in an area where soil-bearing stress limitations could not normally support structures of more than forty floors.

A total of 98 dampers are used. The short walls use 74 dampers of 280 tonnes output force, in diagonal bracing elements, with available deflection of plus or minus 50 mm. The long walls use 24 large dampers, rated at 570 tonnes force with available deflection of plus or minus 50 mm. These long wall dampers use so-called mega brace diagonal attachments, so that the total installed pin to pin length of the damper is 20 meters. Thus, each damper spans several floors of the building, and floors with damper connections are much heavier in construction to accept the high damper point loadings.

The Torre Mayor dampers use low exponent damping in the $V^{.7}$ range, with the frame remaining largely elastic under most expected earthquakes.

Figures 21-23 show the application and the dampers

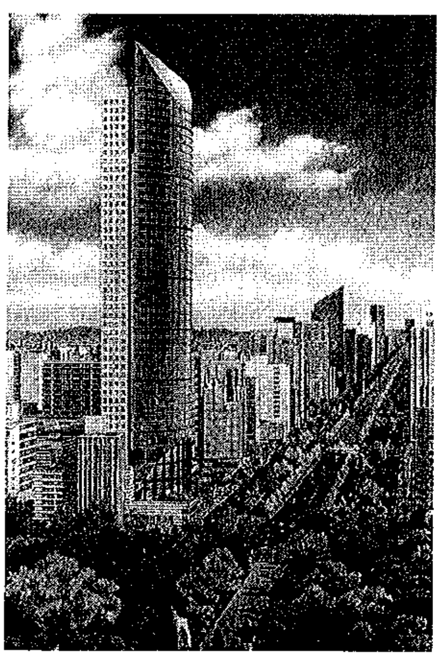


Figure 21. Torre Mayor Office Building

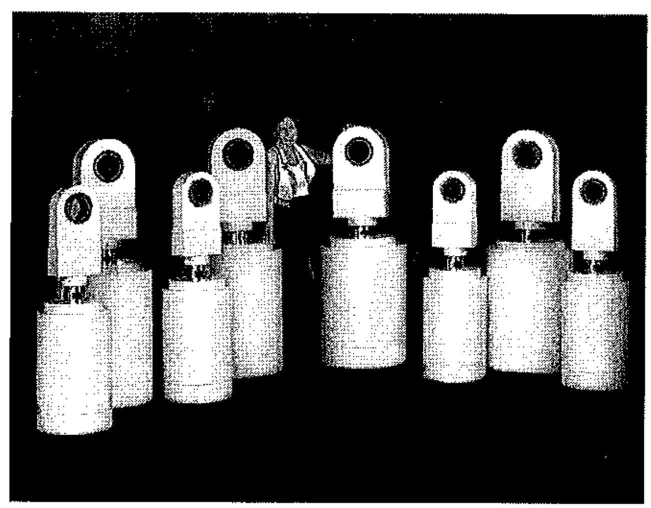


Figure 22. Completed Dampers Torre Mayor Office Building

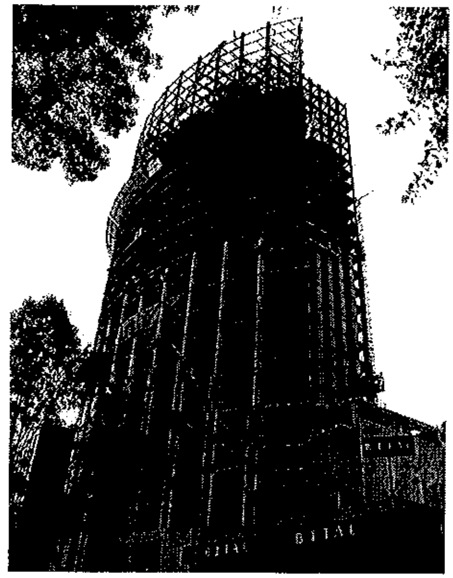


Figure 23. Torre Mayor Office Building Damper Installation

5.4 The Pacific Northwest Baseball Stadium in Seattle, Washington

This major league baseball park opened during the 1999 season, and features a three-section retractable roof, of steel truss construction. When fully extended, the roof measures 192 mm x 200 mm, is 64 m in height, and weighs 10,000 tonnes.

Potential inputs to the roof include U.S. Zone 4 seismic transients and high winds. Added fluid damping was selected at an early stage of the design process to reduce lateral seismic and wind loads to the roof. The reduced loadings from the damped structure reportedly provided a net savings of $4.2 million on the project. Additional dampers were added between roof sections to eliminate the potential for longitudinal pounding damage. The latter application proved mundane, using virtually off-shelf dampers in the 90-180 tonnes force range. The use of dampers in the lateral direction proved much more difficult, since the only available mounting point was to use large dampers in diagonal braces between the column and roof trusses. The dampers were located relatively close to the intersection of these two structural elements, and available mounting regions dictated that a total of only eight dampers could be used. These eight were required to reduce both stress and deflection in the 10,000 tonne roof, requiring that each damper be capable of 500 tonnes output under maximum credible earthquake conditions, with plus or minus 375 mm deflection. The design was made much more difficult due to a 7 m required pin to pin length for the dampers, coupled with a restriction from the architect that would not permit a conventional flange connection between damper and extender. The damper design was further restricted by the architect with a requirement that there be no more than a 25% diameter change at any point along the entire length of the device.

A third restriction on this design was imposed by wildlife in the local environment, namely seagulls and other birds, which would be expected to inhabit the roof truss structure. Seagulls are notorious for having the capability of ingesting practically anything that resembles food, and have evolved a powerful digestive system. Experiments have verified that gull droppings can etch or remove most paints, and can even cause erosion to plated steel. The problem was compounded by the fact that seagulls find shiny surfaces to be attractive, and this is especially true of highly finished piston rods. To address the concern, the large dampers for this project used steel covers over stainless piston rods. The rod covers were combined with a forged stainless steel cylinder which was passivated after machining and heat treatment. Passivation is a chemical process that removes any free iron atoms from the surface of the steel, rendering the steel much more corrosion resistant than plain stainless steel. Passivation also "knocks down" much of the shiny, reflective nature of stainless steel surfaces, leaving a dull finish that will hopefully prove unattractive to birds.

Figures 24-27 show the application and the dampers

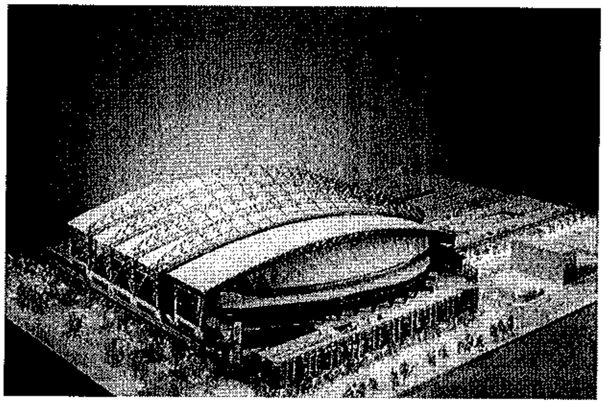


Figure 24. Pacific Northwest Baseball Stadium

Figure 25. Testing on a Damper Cartridge Pacific Northwest Baseball Stadium

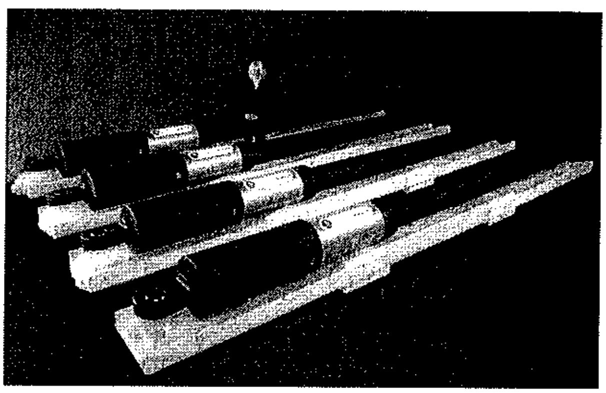


Figure 26. Completed Dampers Pacific Northwest Baseball Stadium

Figure 27. Damper Installation Pacific Northwest Baseball Stadium

6. CONCLUSIONS

The use of fluid dampers for seismic and wind protection of commercial and public structures has occurred widely throughout the 1990's and into this century. Implementation has occurred rapidly, compared with other technologies. This is due largely to the widespread use of fluid dampers on Cold War era defense and military programs. When the Cold War ended, much of the fluid damper technology was declassified and transitioned to the public for commercial use. Very little development was needed to implement fluid damping technology into civil engineering structures, simply because substantial U.S. Government funds had already been spent throughout the Cold War developing optimal damper designs. These were proven through extensive testing and widespread use throughout the military and defense sector.

When fluid dampers are used for seismic or wind protection, the end result is a predictable reduction of both stress and deflection in the structure. This simultaneous stress and deflection reduction is unique to fluid dampers. Optimal performance is dependent on the type of structure and the level of performance required. Damping levels for optimal use of this technology range from 10% critical to 45% critical.

Today, more than 240 major buildings and bridges are using fluid dampers as a primary design element. Damper sizes being used range from as little as 5 tonnes force to more than 800 tonnes force, with deflections as low as 25 mm and as high as 1.5 m. Indeed, it can be said that the use of supplemental fluid dampers will be one of the primary solutions for seismic and wind protection in the structures of the 21st century.

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8. ACKNOWLEDGMENT

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