

VISCOUS DAMPERS:
Practical Application Issues for the Structural
Engineer

by

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Abstract

Only in recent years have fluid viscous dampers (FVDs) been incorporated into building designs and retrofits in the United States to control the seismic and wind response of structures. They have been found to be an effective way of introducing damping to a structure to decrease building displacements. However, in Japan and several other countries, the FVD technology has been incorporated into buildings since the early 1990s and has been used widely on a much smaller scale for decades in the nuclear, mechanical, and automotive industries. In the U.S., this can be due to the idea that much of the work being performed in academic institutions to understand and model their behavior and their interaction with the structure it is attached to is often impractical to the practicing engineer and repetitive, with each researcher deriving their own analytical model for use. There remains no rational methodology for determining the optimal damping for a building, with research focusing more on deriving analytical methods rather than procedural methods, which the practicing engineer is accustomed to. The technology, therefore, remains to be widely accepted or even considered. An attempt is made here to address some of the relevant issues that a practicing design engineer wishing to incorporate FVDs would need to consider. A discussion on the available guidelines for design, other energy dissipation alternatives, and current procedures being followed for FVD design and analysis is provided.

Thesis Supervisor: Jerome J. Connor, Jr.

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1.0 Introduction

Recently, with a general heightened awareness of seismic risks among the structural engineering community, the use of seismic devices in buildings to control the seismic response of a structure is on the rise. This may be, in part, in response to the extensive structural connection and member failures caused by the 1994 Northridge earthquake in California. In light of the Northridge building failures, the fundamental design philosophy of seismic design to depend on the ductile behavior of the structural material to absorb earthquake energy was questioned. Thereafter, despite previous resistance by structural engineers to incorporate the unconventional mechanisms into their traditionally-designed structure, structural control through the use of energy dissipation devices became a more serious option for many designers [13].

Fluid viscous dampers (FVDs), one example of these untraditional energy dissipation devices, only began to be used in buildings in the early 1990s. Since their introduction to the general structures industry to decrease seismic or wind response, fluid viscous dampers have been used and are planned for use in several new and retrofitted buildings in Japan, Italy, Mexico, California, and occasionally in other regions of the U.S. In Japan and, on a lesser scale in Italy, the understanding and implementation of FVD technology as applicable to buildings developed more rapidly than in the U.S. Only in the late 1990s have FVDs been incorporated seriously into building designs and retrofits in the U.S. However, much work has yet to be done to make structural design with devices a viable, generally-accepted alternative to traditional earthquake or wind design.

2.0 Motivation and Scope

In a recent Earthquake Engineering Research Institute (EERI) symposium in San Francisco, Professor Emeritus V.V. Bertero of U.C. Berkeley, pioneer in the area of energy dissipation devices, remarked that there is a dangerously widening gap between academic researchers and practitioners of seismic engineering. He criticizes the “confusing and often redundant research pouring out of academia” [18]. Practicing structural engineers not only cannot keep up with the various research findings, but oftentimes find the results hard to incorporate into their traditional design methods. In the case of the large scale fluid viscous damper, this is compounded by its roots in the nuclear, mechanical, aerospace defense, and automotive industries. Hence, it is no wonder that structural engineers feel that they lack the background and knowledge to design with these energy dissipation devices. The result is the slow integration of this innovative technology into the structural engineering community and a lack of guidance or a consistent design procedure.

The motivation for this thesis, then, is to add cohesiveness to research in order to help the structural engineer design using energy dissipation devices, in particular using fluid viscous dampers. An attempt is made here to address the main issues that need to be considered in design in a way that is relevant to a practicing engineer familiar with the conventional method of lateral load design. Much attention is paid to the computer analysis required for design since currently many design issues are raised in this area due to the lack of appropriate software for damper design. Although viscous dampers may

also be used for wind resistance in tall buildings, this thesis will focus primarily on their effectiveness in resisting seismic loads. Additionally, concentration is on the use of passive viscous dampers throughout the building height, as opposed to their use in active control measures. Limited review of the current guidelines for the structural design with dampers available is also provided. Although the U.S. lags behind Japan in regards to FVD development in the construction industry, all discussions in this thesis are limited primarily to the state of understanding and procedures followed by researchers and practitioners in the U.S. in efforts to be most applicable to structural design as understood and carried out by U.S. design engineers.

3.0 Background Information on Fluid Viscous Dampers

3.1 Description

For the structural engineer unfamiliar with the technology of the fluid viscous damper, a brief summary is provided here, while limited descriptions of the other energy dissipation devices are given in Section 5 only as they are relevant to the understanding of their differences with respect to the fluid viscous damper.

The fluid viscous damper as used in structures works much like a shock absorber works within a car, but on a *much* greater scale. Currently, the primary manufacturer of FVD's in the U.S. is Taylor Devices Inc., based in North Tonawanda, NY [24]. Only recently have Taylor Devices begun manufacturing their FVD to the general construction industry, while previously they manufactured it solely for the defense industry for use in the classified MX Missile and Stealth Bomber [23]. The Taylor Devices' FVD (see Figure 1) consists of a stainless steel piston filled with silicon oil, which is pushed through a bronze orifice. It is the transfer of fluid from chamber to chamber and the resulting pressure difference that provides the damping force.

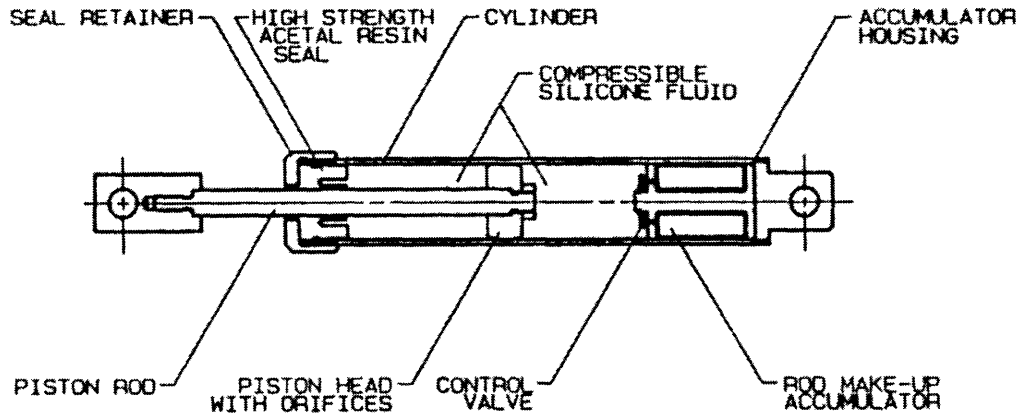


Figure 1: Construction of a fluid viscous damper

At frequencies below 4 Hz, the FVD acts in a linear fashion; that is, they are dependent only on velocity, providing only damping to the structure. Above 4 Hz, they tend to contribute to stiffness as well, as shown by the equation:

$$F + \lambda \dot{F} = C_o \dot{u}^n \quad (1)$$

where F is the output force, λ is the relaxation time, C_o is the damping constant at zero frequency, \dot{u} is velocity, and n is the damping exponent dependent on the shape of the piston head. However, for practical purposes, the $\lambda \dot{F}$ term may be neglected since 4 Hz is usually higher than the frequencies of the dominant modes of vibration for the analyzed structure when subjected to earthquake loads. Additionally, although n may vary for structural applications from 0.3 to 1.0, unless specific response limitations above a given velocity are necessary, structural FVDs are generally designed for a value of $n = 1$.

Dependent on the damper diameter and orifice area, the damping constant, C_o , is the most important variable in this equation. Typically given in units of lb-sec/in, the damping constant is specified by the structural engineer and, along with the maximum

velocity for the building, is sufficient information for the manufacturer to supply the necessary equipment. Depending on the damping requirements of the building, the resulting force may range anywhere from 2 kips to 2000 kips.

3.2 Structural Function and Implementation

When implemented within the lateral load resisting system of a structure, FVDs greatly improve a structure's response to lateral loads. They do this by increasing the damping ratio (ζ) from 2%-5%, typical for buildings, to 20%-30% of critical, which greatly reduces the building's acceleration and displacement. In contrast, at 2%-5% damping, when relying on the inherent damping capability of the structure, the building is relying on the inelastic deformation of its members to absorb the energy transferred to the building by the seismic. FVDs have been used previously for decreasing the structural response for both new building projects and retrofit projects.

The dampers may be installed within the building's height to complement the traditional lateral load resisting system, either along the length of the lateral braces or horizontally at the base or top of the bracing system. For diagonal bracing, they can be installed in different configurations as shown typically in Figures 2 and 3, both of which were implemented in the retrofit of the Stockton City Hall [7]. For chevron bracing, typical configurations are shown in Figures 4 and 5, the latter being the configuration used for the Sacramento Pacific Bell 911 Facility retrofit [7]. Additionally, FVDs may

also be used as an energy dissipator in conjunction with base isolation methods. Figure 6 shows an example of this implementation, as used in the hybrid seismic resistance system of the San Bernadino County Medical Center building complex [2]. Regarding the selection between these different configurations, no further discussion will be provided due to the lack of available research on this issue.

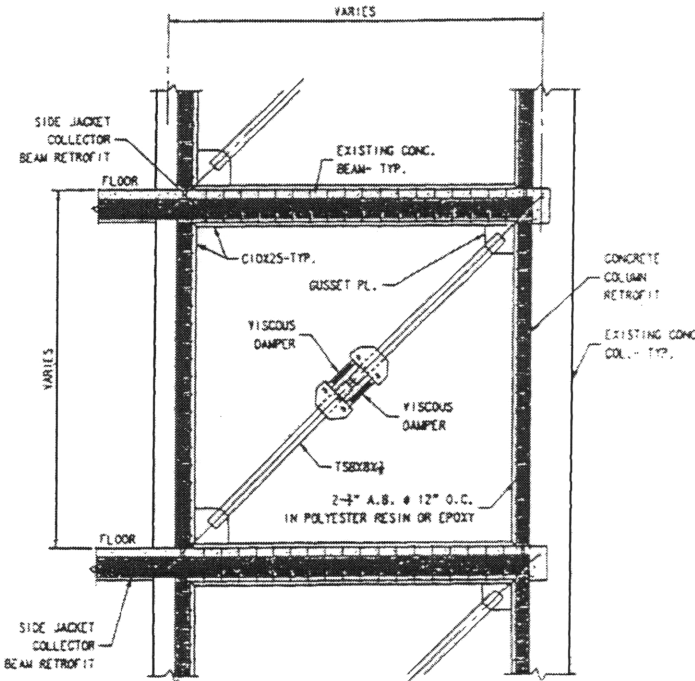


Figure 2: Typical implementation of a FVD with diagonal bracing (1)

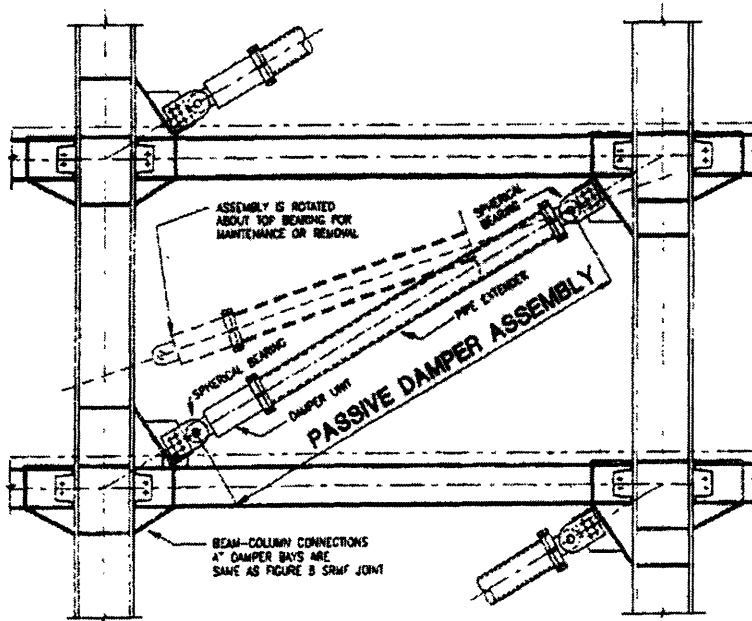


Figure 3: Typical implementation of a FVD with diagonal bracing (2)

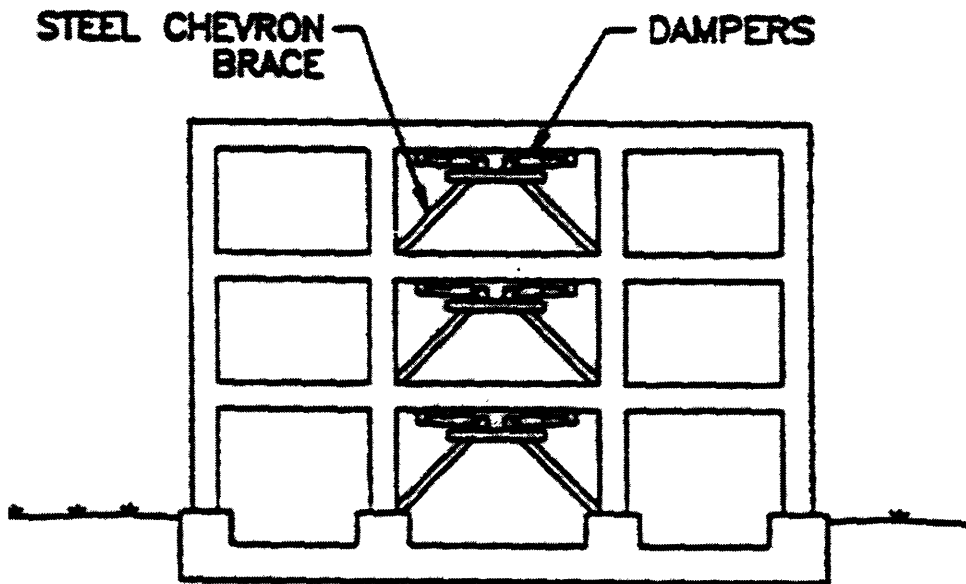


Figure 4: Typical implementation of a FVD with chevron bracing (1)

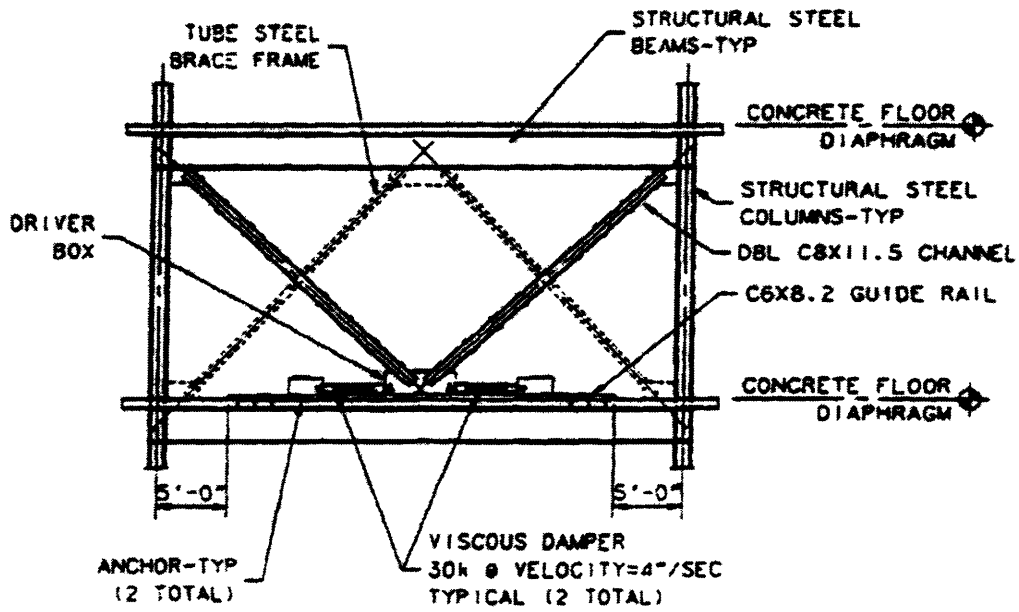


Figure 5: Typical implementation of a FVD with chevron bracing (2)

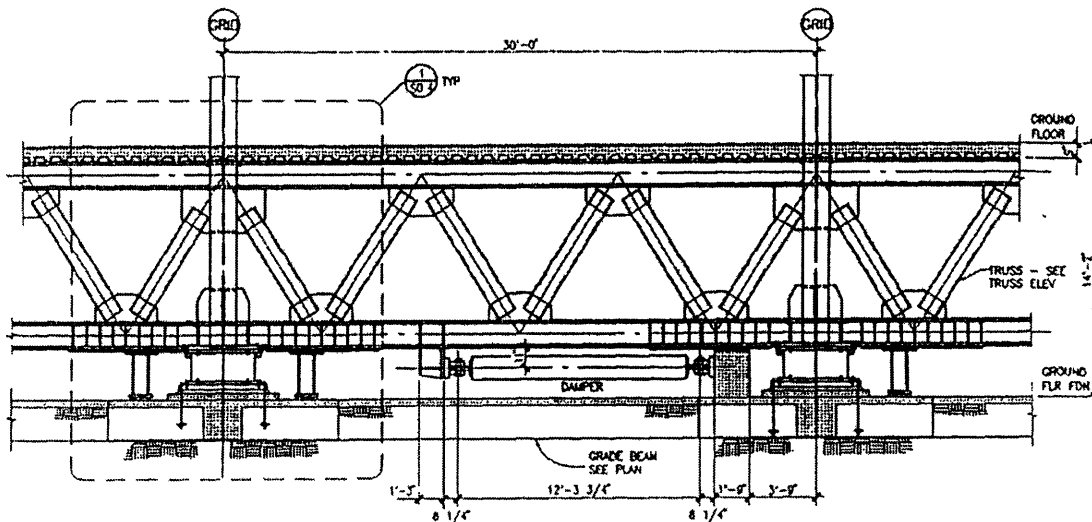


Figure 6: Typical base isolation solution with FVDs

In each case the dampers are typically attached to the structure with a mounting bracket, as shown in Figure 7. Also, spherical bearings are located at the ends of the damper in order to preclude binding within the dampers if the structure it is attached to is too stiff. Located either at both or only one end of the damper attachment, they permit full rotation unrestrained by the behavior of its attached frame.

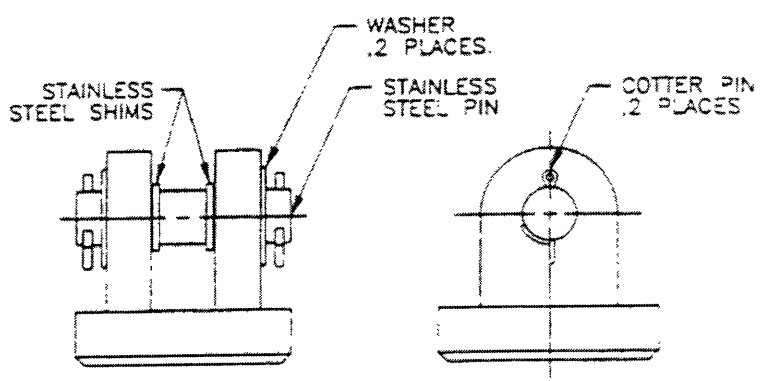


Figure 7: Typical mounting bracket for FVDs

4.0 Selection of Fluid Viscous Damper Solution

The purpose of this section is not to argue for the use of FVDs over the traditional design solution or over other passive energy dissipation devices. Rather, this section is an effort to help the designer choose which solution is the most appropriate for the project being considered.

4.1 Fluid Viscous Dampers vs. Traditional Design

In order to select the fluid viscous damping solution as the appropriate solution for a project, the resulting benefits must obviously outweigh those of the traditional design. Therefore, it is necessary to first define the performance requirements for the building in regards to desired response in the event of an earthquake and as well as in its aftermath.

As previously mentioned, in conventional seismic design, energy dissipation is dependent on the inelastic behavior of its structural components. The amount of hysteretic behavior is dependent on the resulting inter-story displacement. For a typical building, story displacement ratios (story drift/height of floor) of less than 0.003 still act elastically, producing no energy dissipation (Figure 8). However, for greater story drifts, the inelastic deformation of the structural elements occurs. Since inelastic deformation usually involves structural damage to a certain degree, repair of such elements may be necessary [1].

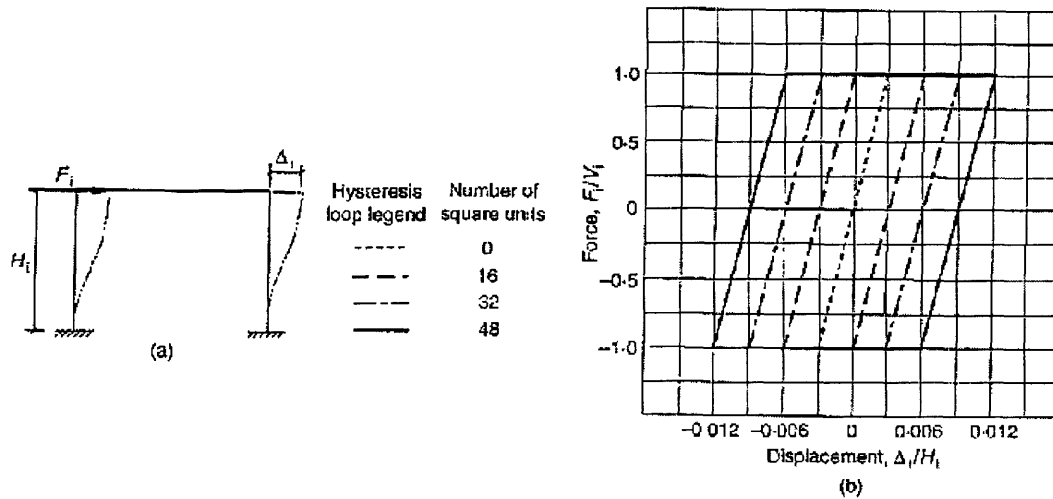


Figure 8: Hysteretic behavior of a typical single story of a conventional earthquake-resistant structure

In conventional seismic design, given that inelastic deformation will occur, members and connections are designed so at least the integrity of the structure is not compromised after an earthquake. After the Northridge earthquake, traditional connection details that were thought to be adequate for maintaining structural integrity were questioned. Many new guidelines for connection detailing were published and much more attention given to their design (e.g. FEMA 267 [9]). However, even with the new details, repairs may still be necessary depending on the extent of inelastic deformation. In contrast, the use of viscous dampers allows the rest of the structure to remain elastic, while the dampers themselves supply the necessary damping to dissipate the energy. Furthermore, they are able to provide much higher damping forces than conventionally designed structures, which in the end leads to smaller building displacements.

Despite the benefit of eliminating repair costs in the future, there usually is a trade-off of higher initial costs. This, however, will vary depending on the project being

considered. At this point in the game, even by those that design with devices, dampers are generally not considered for new buildings since their high costs (according to 1997 values, approx. \$7,000 for a 150-kip damper [17]) do not offset the conventional retrofit costs of merely increasing the strength of the members or ductility of the connections. Exceptions for new buildings may include structures that have high performance requirements, such as those that may apply for critical facilities that need to remain operational such as fire or police stations, hospitals, or bridges. In the case of retrofits, though, the damper option is more attractive. In historic buildings, for example, many times there are limiting architectural restraints, perhaps in the form of space requirements or cladding limitations that make strengthening not possible or if the ductility of the current members is limited. In these instances, the viscous damper solution should seriously be considered and compared with respect to life-cycle costs.

As an example, in the design of the steel pyramid building that was newly built as the national headquarters for The Money Store in Sacramento, CA [13], the advantages and disadvantages of the dampers were weighed. In this case, reducing the displacement caused by earthquake loads with shear walls or bracing would have decreased the fundamental period (T) of the building. It, therefore, would have shifted the building period, as well as resulting building acceleration, to levels that could potentially cause resonant behavior with the short period earthquake loading. In addition, the amount of shear walls needed would have interfered with the space requirements. If conventional bracing were to be implemented, their placement would also be limited since they would cause column forces that are in phase with the frame forces. FVDs, on the other hand, cause forces 90° out of phase with the frame forces, causing no additional strain on the

columns. This is true since FVDs are dependent on velocity, which is zero at the point of maximum displacement causing the FVD force to also be zero at this point of maximum column strain.

The problem of space limitations was also seen in the retrofit of the Los Angeles City Hall [22], where traditional shear walls added to the 24th floor would have increased the acceleration of the floor and caused damage to the exterior facade and emergency telecommunication system. Therefore, FVDs were used on this top floor. On the other hand, for the ground floor of the L.A. City Hall, it was determined that the traditional reinforced concrete walls were more effective. In this case, the conventional solution allowed additional strength to be added to the frame, a redistribution of the overturning forces, and a reduction of the building's period of vibration. For the L.A. City Hall, a reduction in the building's inherent period was actually desirable in order to make the base isolation solution more effective by keeping the structure's seismic response elastic.

In addition to building limitations, when considering FVDs with respect to traditional methods, the additional constraints on conventional retrofitting techniques that have been imposed after the Northridge Earthquake should also be accounted for. In a five-story steel moment frame hospital [7], for example, all 480 moment frame joints needed to be strengthened according to the new requirements. However, by adding FVDs, the resulting flange stress in the beam-columns was so low that they no longer needed to be modified by the Northridge provisions.

4.2 Fluid Viscous Dampers vs. Other Passive Energy Dissipation Devices

Currently, there are four other feasible energy dissipation device options that have been previously implemented in the U.S. – viscoelastic (VE) dampers, one type of which has been developed by 3M Corporation [6]; ADAS dampers, which are a type of hysteretic metallic dampers manufactured by CounterQuake Corporation [25]; friction dampers, one type of which has been developed by Fluor-Daniel; and a hybrid system of energy dissipation/absorption techniques. A brief description will be provided here only in relation to their advantages or disadvantages over fluid viscous dampers.

4.2.1 FVDs vs. Viscoelastic Dampers

Viscoelastic dampers behave much like viscous dampers except they contribute added stiffness, hence requiring a non-linear damping element and non-linear model to define their behavior. They typically consist of metal plates that are separated by a viscoelastic polymer material (acrylic copolymers in the 3M product) which are attached by epoxy to the plates (see Figure 9) and, in some cases, to the structure.

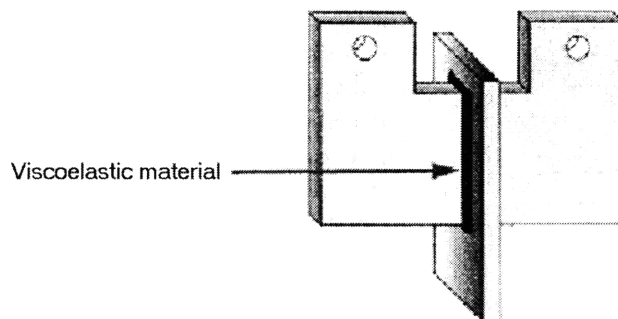


Figure 9: Typical viscoelastic damper

Their drawbacks in the past include unstable behavior under variant temperatures. At low temperatures the force increases greatly causing overloading of the epoxy bond, while at high temperatures the output of the device reduces significantly [24]. This problem is compounded by the fact that they are usually designed using the linear Kelvin-Voigt, elastic spring and dashpot, model, given simply by the equation:

$$F = K u + C \dot{u} \quad (2)$$

It is clear that this model does not account for the VE damper dependence on ambient temperature, excitation frequency, or shear strain damping [8]. Therefore, more complex analytical modeling is needed when designing with VE dampers. Meanwhile, FVD behavior is stable over a temperature range of -40°F to 160°F and do not have welds or bonds that may be overstrained.

In addition, as mentioned previously, FVDs cause column loads that are out of phase with the regular column stresses since they are dependent on velocity alone. Conversely, VE dampers cause in-phase column stresses and, for strong earthquake loads, even high stresses independent of the building displacement.

However, these disadvantages can be designed for and may be outweighed by the necessity of adding stiffness to the building. For instance, additional stiffness may be needed in order to help the structure behave elastically under seismic loads [7]. In addition, research at the Waseda University in Japan [20] supports the use of viscoelastic dampers versus viscous dampers because they have been shown to respond well under unforeseen strong ground motion. Meanwhile, they found viscous dampers to be not as

effective under unexpected medium to strong ground motions since the energy dissipation at this level is dominated by yielding of the system, rather than damping.

4.2.2 FVDs vs. ADAS Dampers

For metallic hysteretic dampers, energy dissipation is achieved by the inelastic yielding of multiple steel plates, as shown in Figure 10. ADAS (Added Damping And Stiffness) dampers are one type of hysteretic damper.

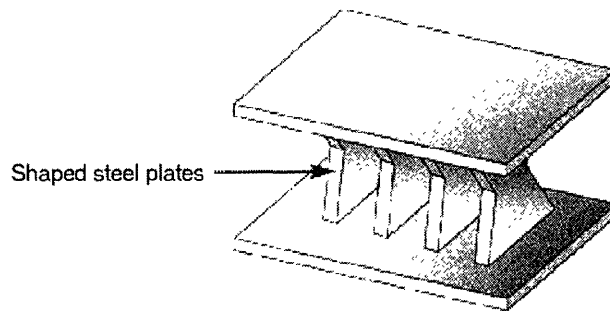


Figure 10: Typical hysteretic damper

They provide both stiffness and damping – contributing stiffness up till the point of metal yielding and damping for more extreme excitations. However, the danger and drawback of providing stiffness is the additional base shear that results because of the stiffening. For example, in the comparative analysis of the retrofit of a 10-story office building in Alameda Park, Mexico City between ADAS dampers and FVDs, the ADAS dampers were able to increase the first floor stiffness by 30%. However, correspondingly, they increased the base shear by 20%. Therefore, in order for the ADAS dampers to be more cost effective, the necessity for additional stiffness must offset the cost of strengthening the structure itself.

4.2.3 FVDs vs. Friction Dampers

Frictional damper technology as used in buildings is much older than that of the FVD, dating back to the 1980s. Stiffness and damping is provided in these devices by frictional sliding between steel plates or between rubber pads and steel plates (Figure 11).

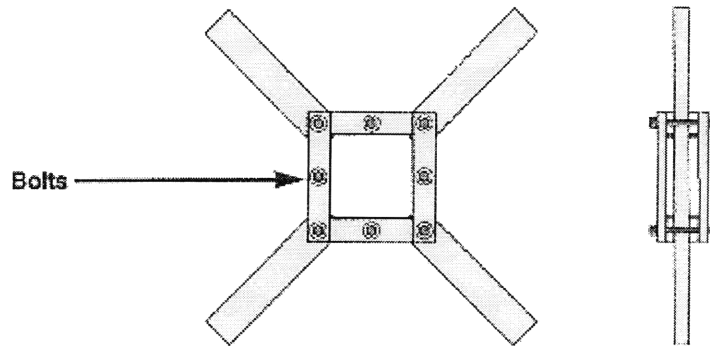


Figure 11: Typical friction damper

Research on this latter form of the friction damper at Cornell University [16] provides insight into the advantages and disadvantages of their use. Since frictional damper forces are dependent on the current value of stiffness, their effectiveness is seen to be dependent on the specific ground motion being applied and the building's period of vibration. Experiments reveal that for seismic loadings with a gradual buildup of acceleration, friction dampers are successful in reducing the maximum story drift and base shear. However, for impulsive type loading, the stiffness of the friction dampers may actually increase the resulting peak displacement and force levels, while the damping contribution would not be large enough to counteract this increase. For friction dampers, this additional damping is usually in the neighborhood of 10%, while for FVDs the dampers provide damping values of around 20%-30%. Therefore, when considering friction dampers versus FVDs, it is important to use time history records that are

representative of the building's region since this will play an important role on the friction dampers' relative effectiveness, keeping in mind that for earthquakes with few, but strong, cycles of excitation, there is little effective damping.

Additionally, since friction dampers are independent of velocity and displacement, under thermal stresses there is a constant force output from the dampers, which then causes continual stresses on the columns which may not be designed for. To make matters worse, these column stresses are also in phase with the regular column stresses. Relative to the FVD, the friction damper also falls short in the area of post seismic conditions since it does not allow the building to return to its original position, but remains deformed.

4.2.4 Hybrid Solution

In many cases, the compromise to the various advantages of each type of energy dissipation devices is to incorporate more than one device into a hybrid design. A hybrid solution is also used to refer to a design that uses more than one method of motion control. This may involve using a base isolation solution in conjunction with viscous dampers located throughout the structure since FVDs have been proven in the past to reduce building displacement; or it may involve taking advantage of the cheaper, traditional stiffening techniques on certain floors and FVDs and/or viscoelastic dampers on others. Therefore, the conventional building design or existing building design must be evaluated with respect to the established parameters in terms of its period of vibration relative to the excitation period from seismic loading, its resulting story drifts, its story

accelerations, its base shear, and overturning moments. When considering a particular damping device to solve one or more of these problems, the effects it may have on the other aspects of building behavior must be considered and compensated for.

For instance, in the design of the San Bernadino County Medical Center in California [2], a hybrid energy dissipation system was used. The base was isolated with linear and non-linear rubber bearings, with viscous dampers added at the plane of isolation as well. Non-linear isolators were included in order to provide lateral stiffness for the base isolation system, which then controls the fundamental period of the building. However, although the building acceleration and forces were reduced, building displacement was still unacceptable. In order to control the displacement, the non-linear bearings would need to be further stiffened, which would then increase the base shear applied to the building. Therefore, since FVDs minimally affect the building period, and therefore the base shear of the building, adding FVDs at the base provides the necessary reduction of displacement without posing additional loads on the foundation.

5.0 Overview of Existing Design Guidelines

Formal guidelines that exist to aid the structural engineer in structural design with dampers are limited. A preliminary design code has been published by the Structural Engineers Association of Northern California (SEAONC) in 1993 entitled *Tentative General Requirements for the Design and Construction of Structures Incorporating Discrete Passive Energy Dissipation Devices* [21]. It is intended to later supplement the SEAOC code as the “Green Book.” While an important step towards developing a consistent design procedure, the code is very limited and general, lacking sufficient detail to aid the engineer in a complete design. It concedes that since the technology is very new, the methods adopted are highly conservative, which may not lead to the most effective damper design. They call for the use of response spectrum analysis, provided that the lateral force resisting elements remain elastic. If nonlinear viscous damper behavior is to be designed for, an additional nonlinear time history analysis is required. They also specify when the Design-Basis Earthquake (DBE) (earthquake forces that have a 10% probability of being exceeded in 50 years) and when the Maximum Capable Earthquake (MCE) (earthquake forces that have a 10% probability of being exceeded in 100 years or sometimes defined with a 2% probability in 50 years) are to be used in different parts of the analysis. They also require that the minimum design base shear be calculated using the response reduction factors, R_w , given in Table 1 and further magnified by the modification factors, α , given in Table 2.

Table 1: Revised Response Modification Factors (R_w) as given in the SEAONC code

Basic Structural System	R_w
Building Frame System	10
Moment-Resisting Frame System	10
Dual System	12

Table 2: Magnification Factors (α) as given in the SEAONC code

Basic Structural System	α
Structural Steel	1.7
Reinforced Concrete	1.4

The code also gives several provisions for experimental testing of the damper set-up and assembly to verify the design if this is considered necessary by the structural engineer.

More practicable provisions are given on the use of control devices in retrofit design, however, in a chapter in the recent FEMA 273, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* recently published in October 1997 [14]. The guidelines specify practical equations for analysis using linear static procedures, linear dynamic procedures, nonlinear static procedures, and nonlinear dynamic procedures. For a viscous damper, using the static procedures, the effective damping, β_{eff} , for the building is taken

as:

$$\beta_{eff} = \beta + \frac{\sum W_j}{4 \pi W_k} \quad (3)$$

where β is the damping inherent in the framing system (generally taken as 5%), W_j is work done by device j in one complete cycle of loading associated with floor displacements δ_i , and W_k is the maximum strain energy defined as:

$$W_k = \frac{1}{2} \sum_i F_i \delta_i \quad (4)$$

where F_i is the inertia force at floor i . Meanwhile, the work done by each device j is:

$$W_j = \frac{2\pi^2}{T} C_j \delta_{rj}^2 \quad (5)$$

where T is the fundamental period of the rehabilitated building, C_j is the damping constant for the device j , and δ_{rj} is the relative displacement between the ends of the device j relative to its axis. The effective damping, β_{eff} , is then used to determine the design forces and moments (collectively called “actions” in the NEHRP guidelines) to be applied to a mathematical model of the building for analysis. The actions to be applied are taken as the maximum of the calculated actions for three deformation stages – maximum drift, maximum velocity and zero drift, and maximum floor acceleration. The forces and moments for the stage of maximum drift are determined traditionally through the distribution of the base shear, V , throughout the building. The effective damping, β_{eff} , is used in this case to find the appropriate reduction factors for the calculated lateral load applied to each floor using Table 2-15 of FEMA 273. (The reader is referred to FEMA 273 Chapter 3 for more details on calculating the design lateral load.) For the stage of maximum velocity and zero drift, the applicable forces include the viscous forces created by the dampers calculated using the relation given by Equation 1 (neglecting the $\lambda \dot{F}$ term), where the relative velocity, \dot{u} , is estimated as

$$\dot{u} = 2 \pi f_1 u \quad (6)$$

where f_1 is the fundamental frequency of the building and u is the relative displacement between the ends of the FVD. In addition, horizontal inertia forces are included in this stage to maintain zero drift for each floor. And finally, at the stage of maximum floor acceleration, the design forces and moments acting on the structure are calculated using the relation:

$$[action]_{\text{max. accel.}} = CF_1 \times [action]_{\text{max. drift}} + CF_2 \times [action]_{\text{max. velocity}} \quad (7)$$

where the combination factors, CF_1 and CF_2 , are given by the following equations calculated using the effective damping, β_{eff} , found by Equation 3:

$$CF_1 = \cos[\tan^{-1}(2\beta_{\text{eff}})] \quad (8)$$

$$CF_2 = \sin[\tan^{-1}(2\beta_{\text{eff}})] \quad (9)$$

It can, therefore, be seen that in order to determine the design actions for the stages of maximum velocity and maximum floor accelerations, it is necessary to first know the value of the damping constant, C_o , of the dampers used. The process is then inherently iterative.

For the dynamic procedures, the corresponding equations for each mode m are:

$$\left(\beta_{\text{eff}}\right)_m = \beta_m + \frac{\sum_j W_{mj}}{4 \pi W_{mk}} \quad (10)$$

$$W_{mk} = \frac{1}{2} \sum_i F_{mi} \delta_{mi} \quad (11)$$

$$W_{mj} = \frac{2\pi^2}{T_m} C_j \delta_{mj}^2 \quad (12)$$

Two linear dynamic methods of analysis are recognized – the Response Spectrum Method, which uses modal analysis to determine building response, and the Time-History Method, which determines building response at every time step using time-history records. Only the significant modes need to be considered in dynamic analysis. The effective damping values for these modes are used in similar ways as the static analysis except, for the stage of maximum drift, the actions may be determined directly from the Response Spectrum Method. However, guidelines as to how to carry out these dynamic analyses are not provided. For instance, for the Response Spectrum Method, no specifications are given as to how to model the building – as a shear beam, as a bending beam, or as a combination of the two.

Based on the amount of redundancy, the guidelines also require that if four or more dampers are used for a given direction and story of a building, the displacements that they are able to sustain under a MCE must equal to 130% of the maximum calculated displacement; otherwise, they shall be designed for 200% of the maximum displacement.

Regardless of the method of analysis used (static or dynamic, linear or nonlinear), it is conceded that resulting values for displacement will be fairly accurate, but internal forces will be too high. Therefore, multiple types of analysis would need to be performed. In general, however, since these NEHRP Guidelines are fairly new, their usefulness can not be readily assessed. At this point, structural engineers who practice seismic damper design refer primarily to academic researchers directly for consultation or are themselves associated with the research.

6.0 Design with Fluid Viscous Dampers

The design of a building with fluid viscous dampers calls for the engineer to prescribe the number, size, location of the dampers required for each floor of the building. These must be selected in a way that will produce the desired, design response. In general, the required damping for the building can be determined through computer analysis. Meanwhile, to select the number and size of the dampers is a matter of cost optimization using the computer analysis results. The placement of the dampers is much more subject to individual judgment but at the same time, however, will affect the number and size required. However, there is no consistent method of design used by engineers, many arriving at the solution through different methods. Meanwhile, the research efforts being published many times offer their own version of what should be the optimal design procedure. In this way, the discussion about the overall design procedure here will address only the common issues, or important variations on these issues, considered by structural engineers in past applications of the technology.

The discussion will begin with a general design procedure that is derived from common steps taken in past designs incorporating energy dissipation devices, particularly as applicable to FVDs. Then more detail will be provided as to how these steps have been carried out in specific past projects.

6.1 Overall Design Procedure

By examining numerous descriptions of the damper design of past projects, the following practical, general design procedure is derived:

- *Establish performance requirements.* Such design parameters include allowable damper displacement and maximum inter-story drift ratio (e.g. taken to be $\frac{1}{200}$ in ref. [13] to preclude damage to non-structural elements) for both the DBE and MCE.
- *Establish the response spectra for the DBE and the MCE.* This may require the determination of site specific response spectra that accounts for nearby fault effects, usually established with the help of geotechnical specialists.
- *Design members using conventional methods.*
- *Perform computer analyses to determine damping requirements.* The structure itself should be ensured to remain elastic during both the DBE and MCE loading after the added damping.
- *Iterate to find optimal damping configuration.* This includes damper size, number, and location.

6.2 Computer Modeling

Once the MCE and DBE loading and performance requirements are established, computer modeling must then be implemented in order to analyze the building's

behavior. Due to the lack of suitable design software for the design using devices, many design firms and researchers have used various methods to accomplish this part of the design. Generally, this is seen to usually involve:

- 3D elastic modeling to obtain static and dynamic properties of the building
- Design of building based on conventional methods
- Time history analysis to determine the necessary story damping coefficient requirements
- Iteration in 3D model to confirm and redesign member sizes
- Additional check using an analytical model (e.g. lumped mass model)
- Perhaps, check and analysis using non-linear methods

However, some firms design first using the lumped parameter model to determine the building's response and use the 3D model to confirm the results. Other variations in the analysis outline above may also be equally legitimate. In order to have a concrete understanding of how this computer analysis is actually carried out, a more detailed discussion on previous applications of damper design in actual buildings follows.

Steel Pyramid Building – Sacramento, CA (1997)

In the steel pyramid building mentioned previously, the use of fluid viscous dampers was thought to be the most effective building design. (*Step 1*) The design began with developing a lumped parameter, or stick, model of the building to determine the necessary total effective damping. Since the period of the building was found to be 2.2

seconds in both principal directions indicating a relatively flexible building, a bending beam stick model was used. A stiffness proportional damping matrix was used for this modal analysis since the dampers were placed in series with the braces. The story damping ratio, β , for each floor was determined by the relation:

$$\beta = \frac{C_o \omega}{2K} \quad (13)$$

where C_o is the damping constant of the dampers used, ω is the circular frequency, and K is the stiffness of the floor. (2) Then a 3-D model was created in order to determine the member forces, the relationship between the bracing stiffness and the dampers, and finally their optimal location. (3) Next, a time history analysis based on the established DCE and MCE was applied on this model using ETABS 6.04, modeling the dampers as discrete link elements. (4) These results were verified by those obtained using the stick model.

Historic Concrete College Building – Southern CA (1996)

For an eight-story, historic concrete administrative building on a southern California college campus [3], the retrofit analysis revealed FVDs again to be the better solution in comparison to the conventional retrofitting techniques and to the use of ADAS dampers. The same computer procedural analysis was used for each option considered. (1) First, a 3-D model was created in SAP90, used for a linear dynamic analysis, using the decided response spectrum. From this, non-linear deformations could be identified and located. Therefore, a nonlinear time history analysis needed to be performed. (3) In order

to do this, the fully populated, reduced, 8 degree of freedom (DOF) stiffness matrix for each direction, $[K_x]$ and $[K_y]$, was obtained from the SAP90 model. The mass matrix $[M]$ was estimated with the assumption of lumped masses, while the damping matrix $[C]$ was assumed to consist of two components – the inherent building damping (proportional to $[M]$ and $[K]$) and the damping provided by the added dampers (not proportional to $[M]$ or $[K]$). (4) Using these matrix formulations, the necessary damping was solved for making use of modal superposition with an in-house time history analysis program entitled VISCOS. The earthquake loading for the time history analysis was generated based on the DBE and MCE response spectra with the help of the program SIMQKE.

Los Angeles City Hall – Los Angeles, CA (1995)

The Los Angeles City Hall retrofit, mentioned earlier, is an example of the complexity involved in the computer analysis of a hybrid energy dissipation system. The hybrid system involved using traditional reinforced concrete walls at the base of the building, base isolating the building, and adding supplemental dampers at the 24th floor. (1) The design firm used ETABS to model the building and obtain its linear, dynamic properties. (2) Obtaining the stiffness matrix $[K]$ from this analysis and using the MCE and DBE response spectra, a lumped parameter model of the base isolated building (LPM-BI) was generated. The non-linear response of the structure could then be analyzed and the resulting forces obtained. (3) The results of the LPM-BI analysis were further checked using a model created in 3D-BASIS. (4) Once verified, the forces obtained from the LPM-BI are subsequently applied to a 3-D model created in SAP90.

The SAP90 analysis is used to determine the member forces and overturning moments that would be created by the base isolation solution. (5) Iteration within SAP90 was then performed, each time removing and relocating the isolation bearings until the system was stable.

San Francisco Civic Center State Office Building – San Francisco, CA (1996)

In the design of a new 14-story office building part of the San Francisco Civic Center Complex [10], various damper designs were considered including viscous dampers, hysteretic dampers, and viscoelastic dampers. (Steps 1&2) The design procedure for linear viscous dampers ($n = 1$) is similar to the general method outlined above, where ETABS was used for the 3D elastic model and time history analysis and Drain2DX was used to create the nonlinear model that confirms the linear model results. (3) In this case, the 3D model was used to develop a lumped mass model that was used in the time history analysis and to determine the story damping coefficients. (4) Here, the story damping coefficients were determined through iteration until the beam plastic rotations became acceptable, estimating hinge rotation based on story drift. (5) However, because of the limitations in software, in order to analyze the building using the other dampers ($n = 0.1$ effectively for hysteretic dampers and $0.1 < n < 1.0$ for non-linear viscous devices) it was necessary to use another procedure entirely in order to adequately model the non-linear behavior of the dampers. The program SADSAP alone was used to model a lumped mass

model with non-linear dampers and non-linear structure characteristics and to determine the damping coefficients.

From the examples cited above, it can be seen that each design firm finds a their own way to solve the problem of computer analysis for designing these dampers. In each method, however, more than one computer program is required for complete design, oftentimes being especially written by the designers for the analysis. It is obvious, then, that the time necessary to perform these analyses is limited by the computer software and capabilities available. Therefore, although the different procedures all result in adequate designs, software is needed that is more efficient and better “suited to design office production schedules and fee structures” [10].

6.3 Optimal Damper Placement

In order to effectively model the building with the linear FVDs, it is necessary to already know the placement of the dampers throughout the building. However, in order to optimally place the dampers, the response requirements of the system needs to be known. Therefore, if optimal damper locations are to be determined, iterations of the computer analysis is inevitable.

Little guidance is provided and little practical research has been done to help the engineer decide where the FVDs are to be placed and how often they are needed. Section

A1(c) of the SEAONC design code [21] requires that the dampers be placed on every floor of the building in order to have a continuous vertical line of dampers from the base to the top of the building. However, for extremely tall high-rise buildings, this may not be practical since each damper is so expensive. Therefore, more efficient methods for determining damper placement throughout the building should be instituted. In the meanwhile, because engineers in the past have approach this problem differently, a few of these approaches will be addressed here.

In terms of academic research on the matter of damper placement, the work that is being done is very limited in its practical application. Research at the State University of New York at Buffalo by R.H. Zhang et. al, in the past, focused on coming up with a mathematical design algorithm for determining the optimal location of *viscoelastic* dampers [22]. However, the conceptual basis of the methodology can be extended to also apply to selecting optimal damper locations for viscous dampers since the basic theory remains true for both types of controllers. This theory is that the devices are most effective when placed at locations where the displacement or relative displacement is largest. The results of the research is a mathematical iterative approach to determine optimal damper locations using a multiple degree of freedom model for the structure. Its basic idea is to first design the dampers as if they were located at adjacent floors and then to reduce the number by placing them only at the optimal locations. The optimal location is based on the maximization of the controllability index given by:

$$\rho(x) = \max \sqrt{\sum_{i=1}^n \left\{ \frac{\Delta[\phi_i(x)]}{\Delta x} Y_i(t) \right\}^2} \quad (14)$$

where $\rho(x)$ is the location index at position x , $\Delta[\phi_i(x)]$ is the spatial difference from position x_j to x_{j+1} , $\Delta x = x_{j+1} - x_j$ or the difference in adjacent story heights, and Y_i is the spectral displacement of the applied earthquake at the i^{th} modal frequency. This controllability index is determined using a transfer matrix formulation in order to model the dynamic and multi-modal characteristics of the system. Unlike previous methods where optimal locations are all determined using the uncontrolled structure after a single matrix analysis, an iterative approach is used. This approach is based on the idea that after one controller is added to the system, the entire system characteristics are altered and need to be re-determined to find the next optimal location – hence, the iterations required. As a case study, Zhang et. al presents the following optimal locations for dampers for a typical 24-story structure as found using the procedure outlined:

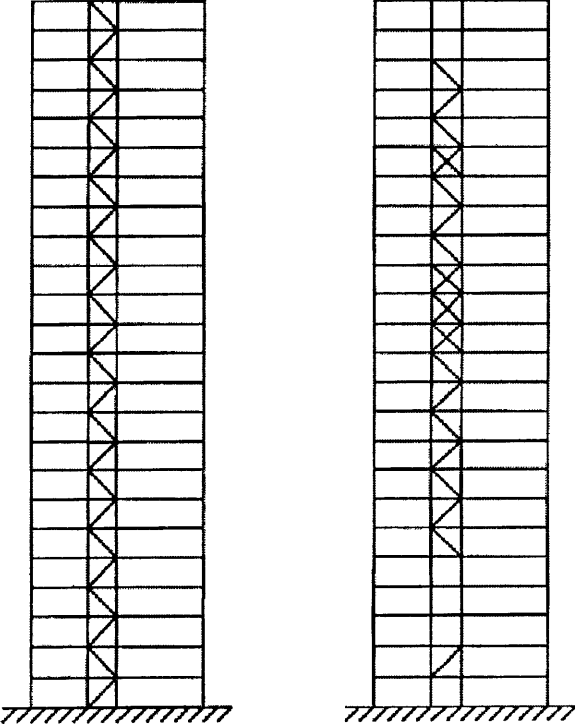


Figure 12: Distributions of dampers (a) fully damped (b) optimally placed

However, for practical purposes, this formulation, though simplified, may still be too mathematically complex to be implemented into the traditional design methods. Regardless, the overall methodology and selection process can be understood and used to determine damper placement. Using the dynamic computer analysis programs in a manner described above, the locations of maximum displacement or velocity can be determined. Once locating the first maximum displacement, the first damper may be modeled and placed at that location and the analysis re-run. This process can then be repeated until the desired structural response for all the floors is achieved, granted that for very high structures this may become rather tedious.

For the design of the 57-story Chapultepec Tower in Mexico City, Mexico, the engineers in charge of the project handled the damper placement issue slightly differently [15]. Firstly, the underlying theory of placement is that the most efficient use of the damper is at maximum differential velocity, rather than displacement as in the case above. However, their approach is to increase the differential velocity experienced by the damper for a *given* inter-story drift and velocity, rather than selectively placing them at the locations of maximum differential velocity themselves. They do this by reversing the orientation of axial velocity of the columns of the frame that the dampers are connected to; in other words, they placed the dampers between two different lateral load resisting systems (for the Chapultepec Tower, there are 3 different seismic systems for redundancy). Therefore, if optimal placement with respect to which floor of the structure the dampers should be placed is not possible, the relative velocity that a single damper can experience can be maximized just by changing the construction configuration with

which it is placed in the building. For the Chapultepec Tower, this is done by using the configuration shown in Figure 13, which contributes additional velocity from both vertical and horizontal “shearing” of the building.

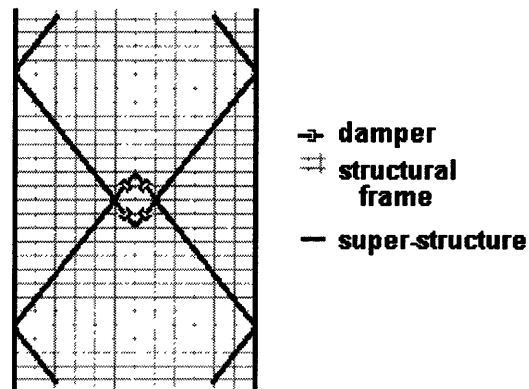


Figure 13: Diagram of Chapultepec Tower damper placement configuration

In the case of a retrofit, however, there may be space or architectural limitations that prevent the dampers to be located at their optimal location. This is usually the controlling factor when engineers decide on damper placement. In the retrofit of the Resources Building in Sacramento, CA, the resulting solution needed to respond to the limitation of space as well as of the existing structural layout [11]. In this situation, the amount of extra loading imparted to the foundations and columns were considered. Therefore, the location and orientation of the dampers and braces were designed to transfer the additional loads to the stronger perimeter columns – located in the Resources Building at every third bay. As shown in Figure 14, they are also staggered in order that the overturning moments on one floor will be counteracted in part by those from the floor below. Here, the controlling factors in damper placement are much more practical in

nature. In this way, for efficient damper placement in a retrofit, the limitations of the existing structure must also be considered. Optimal damper placement, therefore, must take into account more than just the optimal behavior of the dampers themselves.

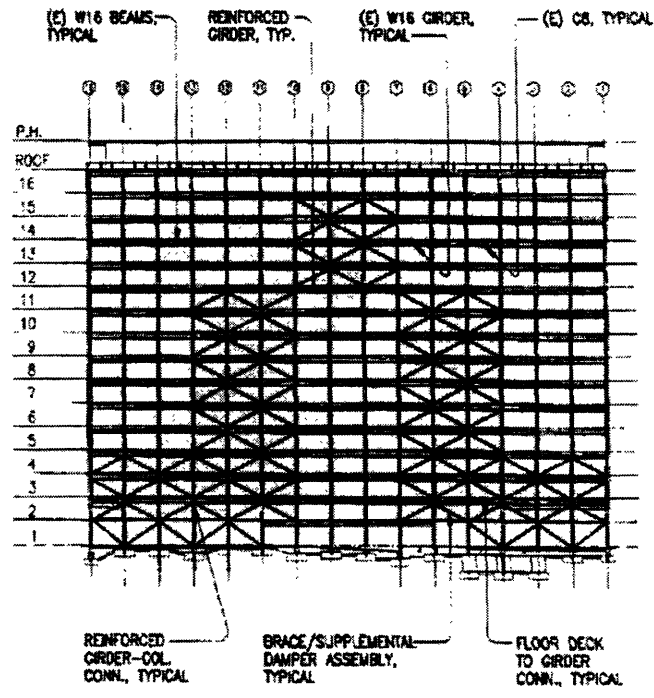


Figure 14: Elevation showing damper placement in the Resources Building (Sacramento, CA)

7.0 Conclusions

The addition of fluid viscous dampers can, therefore, be seen to be a great advantage especially in building retrofits. However, many limitations for the design firm exist regarding their analysis and design. Although their usage has been increasing in the past year alone with many new projects being planned, computer software limitations and the redundancy and impracticality of academic research in this area continue to make it difficult for the design engineer to incorporate FVDs into their buildings. Currently, though, the structural engineers that do design with FVDs seem to have a direct relationship with the university, some even being professors themselves. In this way, the information and benefits regarding the use of dampers are not being disseminated into the wider structural engineering community, but continue to remain within the academic realm. Much collaborative and open work needs to be done in order to make the technology of the fluid viscous damper a real option for the structural engineer. In the same way, it is also the responsibility of the structural engineer to remain current in his/her technical understanding of construction innovations. Going a step further, even more collaboration needs to occur among structural engineers, researchers, software engineers, and architects before the *architectural* benefits of energy dissipation devices can be fully realized. Ultimately, the use of FVDs within buildings can be used to define the architectural purpose of a building design, rather than just to remediate its structural problems. This is stated best by Mies van der Rohe in his postulation about the purpose of technology in general that:

“Whenever technology reaches its real fulfillment it transcends into architecture.”

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