VISCOUS DAMPER DEVELOPMENT AND FUTURE TRENDS

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SUMMARY

Viscous dampers can protect structures against wind excitation, blast and earthquakes. Viscous damper technology originated with military and aerospace applications. Approximately 10 years ago it was found that the same fluid viscous dampers that protect missiles against nuclear attack and guard submarines against near-miss underwater explosions could also protect buildings, bridges and other structures from destructive shock and vibration. This paper describes fluid damper technology, analysis considerations, installation methods and development work in progress.

1. INTRODUCTION TO FLUID DAMPER TECHNOLOGY

Conventional structures absorb earthquake energy through yielding or failure of construction materials. For example, earthquake energy is absorbed when steel beams and columns form plastic hinges, or when concrete structures crack or *URM* (UnReinforced Masonry) structures fail their infill. Viscous dampers offer an alternative to structural yielding or failure as a way to absorb earthquake energy. Viscous dampers can absorb almost all the earthquake energy, leaving the structure intact and ready for immediate use after an event.

Viscous dampers provide a force that always resists structure motion. This force is proportional to the relative velocity between the ends of the damper. The damping law is as follows:

$$F = CV^N \tag{1}$$

where

F is the damper force
C is an arbitrary constant (C remains constant over the full range of velocities) V is velocity
N is an exponent that can range from 0.3 to 1.95 (N remains constant over the full range of velocities)

Notice that there is no spring force in this equation. Damper force varies only with velocity. For a given velocity the force will be the same at any point in the stroke. As dampers provide no restoring force the structure itself must resist all static lateral loads.

Figure 1 shows a typical damper. A central piston strokes through a fluid-filled chamber. As the piston moves it pushes fluid through orifices around and through the piston head. Fluid velocity is very high in this region so the upstream pressure energy converts almost entirely to kinetic energy. When the fluid subsequently expands into the full volume on the other side of the piston head it slows down and loses its kinetic energy into turbulence. There is very little pressure on the downstream side of the piston head compared with the full pressure on the upstream side of the piston head. This difference in pressures produces a large force that resists the motion of the damper.

Viscous dampers, when correctly designed and fabricated, have zero leakage and require no accumulator or external liquid storage device to keep them full of fluid. They have nearly perfect sealing. In a correctly designed and fabricated viscous damper there is nothing to wear out or deteriorate over time so there is no practical limit on expected life. Warranty periods of 35 years are common. All materials in the damper including the working fluid must be nontoxic and nonflammable. In most cases silicone-based fluids are used to insure proper fluid performance and stability.

2. ELEMENTS OF A TYPICAL VISCOUS DAMPER

The following elements form a typical viscous damper as shown in Figure 1.

2.1 Piston rod

The piston rod is machined from high alloy steel stainless steel and then highly polished. This high polish provides long life for the seal. The piston rod is designed for rigidity as it must resist compression buckling and must not flex under load, which would injure the seal.

2.2 Cylinder

The cylinder contains the working fluid and must withstand the pressure loading when the damper operates. Cylinders are usually made from seamless steel tubing and are sometimes machined from steel bars. Proof pressure is generally 1,5 times expected internal pressure for the maximum credible seismic event.

2.3 Fluid

Structural applications require a fluid that is fire-resistant, nontoxic, thermally stable and that will not degrade with age. Under current OSHA (Occupational Safety & Health) guidelines this means a flash point of at least 200^{o}F. Silicone fluid is often used as it has a flash point over 650^{o}F and is cosmetically inert, completely nontoxic and one of the most thermally stable fluids available.

2.4 Seal

The seal must provide a service life of at least 35 years without replacement. As dampers often sit for long periods without use, the seal must not exhibit long-term sticking or allow fluid seepage. The dynamic seal is made from high-strength structural polymer to eliminate sticking or compression set during long periods of inactivity. Acceptable materials include Teflon A, stabilized nylon and members of the acetyl resin family. Dynamic seals made from structural polymers do not age, degrade or cold flow over time.

2.5 Piston head

The piston head attaches to the piston rod and effectively divides the cylinder into two separate pressure chambers. This space between the outside diameter of the piston and in the inside diameter of the cylinder forms the orifice. Very often the piston head is made from a different material than the cylinder to provide thermal compensation. As the temperature rises the annulus between the piston head and the cylinder shrinks to compensate for thinning of the fluid.

2.6 Accumulator

The damper shown in Figure 1 uses an internal accumulator to make up for the change in volume as the rod strokes. This accumulator is either a block of closed-cell plastic foam or a movable pressurized piston, or a rubber bladder. The accumulator also accommodates thermal expansion of the silicone fluid.

3. HOW DAMPERS DECREASE THE EARTHQUAKE RESPONSE OF A STRUCTURE

Viscous dampers add energy dissipation to a structure, which significantly reduces response to earthquakes, blasts, wind gusts and other shock and vibration inputs. Figure 2 shows a standard set of UBC (Uniform Building Code) curves for a structure as a function of period and percentage of critical damping. A value of 30% of the critical value is a practical upper limit for combined viscous and structural damping. Around 25% of this is viscous damping and the remaining 5% is structural damping. This provides a 50% reduction in structural response compared with the same structure without viscous dampers. Note that the addition of viscous dampers does not change the period of the structure. This is because viscous damping is 90 degrees out of phase with the structural forces.

Figure 3 shows a typical plot of base shear against interstory drift, taken from a laboratory test. Note that the hysteresis loop is very flat and thin as there is only 5% damping. Figure 4 shows a plot of the same structure with the same input only this time with added viscous damping. Note that interstory drift is 50% less and that the hysteresis curve is much fuller. The area inside the hysteresis loop is the same as in Figure 3.

It is theoretically possible to provide enough viscous damping to completely prevent plastic hinging. This provides a totally linear structure. Economically, it is best to retain some plastic hinging as this results in the least overall cost. Viscous dampers still limit interstory drift sufficiently to provide immediate occupancy after a worst-case event. They also limit and control the degree of plastic hinging and greatly reduce base shear and interstory shear.

4. THE EFFECT OF DIFFERENT VALUES OF N, THE DAMPING EXPONENT

Figure 5 shows a plot of force against velocity for several values of N, the damping exponent. A value of N = I is the curve for linear damping, which is a good place to start in the design of a damping system. The hysteresis loop for a linear damper is a pure ellipse, as shown in Figure 6. N = 0.3 is the lowest damping exponent normally possible. Figure 5 shows how this value provides significantly more force at lower velocities than a linear damper. Figure 6 shows the almost rectangular shape of the hysteresis curve for this value of N. Structural dampers always use N values between 0. 3 and 1.0, as any value above 1 .0 produces very poor performance.

Linear damping is easy to analyze and can be handled by most software packages. Also, linear damping is unlikely to excite higher modes in a structure. Another advantage of linear damping is that there is very little interaction between damping forces and structural forces in a building. Structural forces peak when damping forces are zero. Damping forces peak when structural forces are zero. Between these points there is a gradual transfer of force. This is shown in Figure 6. Nonlinear damping with a low exponent shows a much more rectangular hysteresis curve and the damping forces tend more to superimpose on the structural forces In addition, nonlinear damping can possibly excite higher modes in a structure.

5. ANALYSIS

Analysis of a structure with dampers generally uses a computer program such as SAP or E-Tabs (available from Computers & Structures Inc 1995, University Ave #540, Berkeley, CA 94704-1070 510-845-2177, U.S.A.). Both of these programs in their latest versions can handle nonlinear dampers as discrete elements.

The first step in the analysis is to find out how added damping affects the structure. This is generally done with a simple stick model with one node for each story. Adding global damping to the stick model provides a good indication of how damping elements can benefit the structure. The analyst will then construct a simple two-dimensional model of the structure. In this model the dampers are entered as discrete elements. At this point there are a number of variables to play with: force capacity of the dampers, location and number of dampers, damper coefficient and damper exponent. The analyst has the task of finding the best solution. This is generally a trial-and-error process but there are some general guidelines. It is always best to minimize the number of dampers and the number of bays that use dampers. Also, we know from experience that approximately 20% to 30% of critical damping is a desirable range, and that 5% of this can be structural, leaving 15%-25% for viscous damping. So the first objective of the analyst is to determine the smallest possible number of dampers to provide approximately 20% critical damping without overloading either the beams or the columns. Also, it is always best to start with linear dampers and then find out what happens with nonlinear dampers after the locations, number and characteristics of the dampers have been fairly well determined.

If a structure is regularly proportioned and its centre of gravity is close to its geometric centre then a more complete two-dimensional model is probably sufficient. If a structure is torsional the analyst will proceed with a three-dimensional model and repeat the analysis.

Note that analysis of a structure with dampers always involves a step-by-step time-history simulation. Sometimes a time-history is not available for a particular location but a shock spectrum is. In this case, a time-history can be arrived at by going through a library of time histories, comparing their shock spectra with the specified shock spectrum at the site and selecting the one that fits best.

6. DAMPER INSTALLATION IN A STRUCTURE

Dampers can be installed in parallel with base isolators, as diagonal members, as part of a chevron brace, horizontally at the top of a chevron brace, or horizontally between adjacent structures. It is also possible to use a linkage system to amplify damper motion. This arrangement is called a toggle brace and is used in structures that have very little deflection under dynamic loading.

6.1 In Parallel with Base Isolators

While both friction pendulum and elastomeric base isolation systems can have some damping, this is often not enough. Addition of fluid dampers, as shown in Figure 7, can cut predicted motion in half. This is very useful in structures where moat space is limited or where the base isolators would have to be extremely large. The viscous dampers also reduce interstory drift and shear.

6.2 Diagonal Member

A viscous damper attached to a tubular extender can be installed almost like a conventional diagonal brace. Unlike a conventional brace, the damper does not change the period of the structure. Figure 8 shows this type of installation, which is extremely effective for refurbishments.

6.3 Chevron Brace

Figure 9 shows dampers installed in both legs of a chevron brace. The effect is similar to dampers in diagonal members.

6.4 Horizontally at the Top of a Chevron Brace

Figure 10 shows dampers installed horizontally to a conventional chevron brace. The apex of the brace does not tie into the adjacent beam but instead drives the two dampers.

6.5 Horizontally Between Adjacent Structures

When two structures are very close together they can pound during an earthquake. Addition of dampers across the gap can greatly reduce earthquake-induced motion and eliminate this problem (see Figure 11).

6.6 Toggle Brace

It is difficult to provide conventional damping when structural deformation is very small, such as less 1/8 in. In this case a toggle linkage such as the one shown in Figure 12 can amplify the damper motion effectively.

6.7 Development Work in Process

A number of companies are working on 'smart dampers' with an electronically controlled damping coefficient. These dampers can alter their degree of damping to minimize the dynamic response of a structure. Smart dampers can use solenoid valves to change damping in steps or they can use rheological fluids to provide continuously variable damping. As smart dampers require external power and control systems they must be designed to exhibit 'fail-safe' behavior in the event of a power failure.

Taylor Devices is working on a damped moment frame connection that has no bracing. This provides all the advantages of moment frame open construction plus the advantages of a highly damped structure. We are also working on an improved toggle brace with much higher motion amplification.

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