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Testing Procedures for High Output Fluid Viscous Dampers Used in Building and Bridge Structures to Dissipate Seismic Energy

Today's economic climate demands that conversion of military technology for commercial applications be a part of an aerospace and defense company's strategic planning. Toward this goal, a successful defense conversion has occurred recently with the application of high capacity fluid damping devices from the defense community for use as seismic energy dissipation elements in commercial buildings, bridges, and related structures. These products have been used by the military for many years for attenuation of weapons grade shock, typically applied to shipboard equipment or land based strategic weapons. Commercial energy dissipation devices historically have involved heavy yielding sections or hysteretic joints.

INTRODUCTION

Fluid damping devices have been used to improve and modify the performance of military equipment, most often to attenuate the effects of weapon's grade shock and blast effects. Most of the concepts, applications, specifications, and designs associated with defense and aerospace use of fluid damping technology have not been publicized, save for occasional article distributed within this community. For example, US Navy shock test requirements are defined by MIL-S-901D (1989). This document is approved for unlimited distribution, but must be obtained through government sources, and would not be expected to be read by an architect or building designer.

A commercial application contemplated for this technology is to use fluid damping devices within building and bridge structures to attenuate the shock loadings associated with earthquakes. It is relatively easy to demonstrate by analysis that damping in a large structure is of substantial benefit to the structure. In addition, extensive experimental results documenting the improved response of highly damped steel building frames have been performed by Constantinou and Symans (1992). Similarly, the long-term prior usage of these products by the military has verified their reliability and affordability. An additional problem involves the test methods and procedures that can be utilized to test full sized hardware. These methods not only have to be acceptable

Received March 7, 1995; Accepted April 28, 1995.

Shock and Vibration, Vol. 2, No. 5, pp. 373–381 (1995)

CCC 1070-9622/95/050373-09

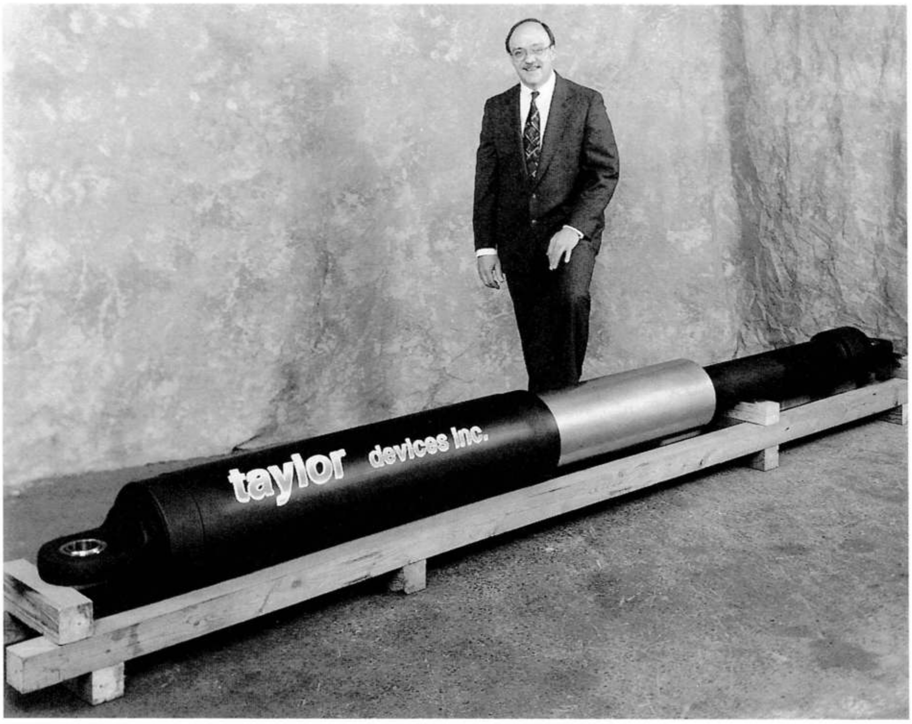

FIGURE 1 Full sized 330,000 lb output damper.

to the structural engineering community from a technical viewpoint, but also have to be available at reasonably low cost.

Fluid damping devices for building and bridge use are relatively large, having output forces in the range of 100,000–2,000,000 lb per device. This article discusses the test methodology and procedures developed for an application within the buildings of a medical center complex in Southern California. The fluid dampers built for this project have a damping output force of 320,000 lb each, with an available displacement of 48 in. A total of 233 of these dampers are being used to provide the buildings in the medical center with damping levels on the order of 35% of critical. The isolated buildings are designed to be free from damage at peak seismic transnational velocities up to 60 in. The test method selected for these dampers was based on military shock test techniques. Figure 1 is a photograph of the full sized 330,000 lb output force damper.

DESIGNING FOR SEISMIC ENERGY DISSIPATION WITHIN A BUILDING OR BRIDGE STRUCTURE

In general, various structural codes are used in commercial building and bridge designs to define the level of protection necessary when a structure is located in an area of possible seismic activity. Depending on end use, customer specified requirements, and the structural codes, a design can be analyzed using either seismic design level shock spectra, or transient analysis techniques. Unlike military applications, seismic motion is largely in the horizontal plane, a loading direction that induces both shear and bending moments into the structure. The vertical motion from an earthquake normally is only a fraction of the level of the horizontal and occurs in a direction in which the structure is strongest, because it must support its own 1-G weight. In a military application, shock inputs occur at levels usually exceeding 30 G, so an extra 1 G would be of little consequence. With earthquakes, the strongest horizontal shaking rarely exceeds 1 G, but this is enough to destroy most buildings or bridges that were not constructed using seismic design criteria. Thus, most seismic designs concern themselves with horizontal inputs only, and provide little or no attenuation in the vertical plane. Constantinou and Winters (1993) provide an evaluation of representative seismic response spectra.

Once the engineer has determined the seismic input, a decision must be made as to whether the building is to be of fixed base or base isolated construction. If a fixed base design is selected, such as would be used in a tall building, the building must be either physically strengthened or tuned, thereby respectively resisting or attenuating the seismic input. In some cases, various types of energy dissipation devices must be incorporated into an internal bracing system to reduce the seismic deflection of the structure, thus preventing yield under the seismic input.

If a base isolated design is selected, such as would be used in a relatively short (less than 12 story) steel or reinforced concrete structure, the building need only be made strong enough to resist the loading on the output end of the base isolation system. The base isolation system consists of sliding elements, such as steel slider bearings or elastomer bearings, and energy dissipation devices to provide damping. Base isolation is common within the defense community. Taylor and Lee (1989) provide typical isolation component descriptions. Clements (1972) and Mosher (1991) provide representative shock spectra and test results.

In general, a steel frame building or bridge will have structural damping levels in the 1–5% critical range; a concrete structure normally has higher damping in the range of 3–8%. Some seismic design approaches over the years have used energy dissipation devices that raised damping levels to the 10–15% range as a reasonable way of reducing stress within the structure. However, with the advent of compact fluid damping devices, it is practical to increase damping to levels to the 20–40% range, offering rather dramatic stress reductions with relatively small damping devices. It is most significant that the requirement for seismic design in buildings is not new, but rather goes back thousands of years. For example, the Parthenon, a well-known structure in Ancient Greece, was actually an isolated structure, with the building columns connected with lead covered wood dowels, providing both low frequency and energy dissipation!

FLUID DAMPER DESIGNS FOR SEISMIC ENERGY DISSIPATION

Fluid damping devices are well proven by the test of time, with production of dampers in the 50 kip range dating to the mid-1890s. The earliest well-documented use of large fluid dampers was by the military, to attenuate recoil transients on large caliber artillery pieces. An early example is the French 75-mm artillery piece, Model M1897, which was in service with various nations in the period 1897–1945. This weapon utilized variable orifice fluid recoil dampers with a pneumatic spring to return the buffer and the weapon to its battery position after each firing.

For testing purposes, fluid dampers can be classified into three groups, depending on the operating design of the internal orifices used.

Viscous-Shear Dampers

Viscous-shear dampers produce an output by viscous shearing of the fluid, and can operate only at relatively low damping fluid pressures. Typically, maximum pressure is less than 300 psi, making this type of device rather large and cumbersome. Output generally follows the classical equations for viscous fluid shear, where shear stress is proportional to speed. This results in the so-called "linear" or "viscous" output, where damper force is proportional to velocity. The major drawback of viscous shear dampers is a strong temperature dependency. Over a typical north central US outdoor temperature range of −20 to +120°F, fluid viscosity changes of between 10 and 30 to 1 are common. This large viscosity change has a direct effect on damping forces.

Inertial Fluid Dampers

Inertial fluid dampers produce an output by forcing fluid through orifice passages. The output force of this type of damper is dependent on the size and shape of the orifices. Operating pressures of 2,000–10,000 psi are common, thus minimizing the effect of fluid viscosity changes, because high inertial fluid pressures dominate the output. Inertial fluid dampers have an output force that follows the Bernoulli equation, where output force varies with the square of the damper stroking speed, and directly with the fluid density. Various mechanical construction means are used to "shape" or "tune" the output force of the damper to a specific function. These means often involve rather complex combinations of spaced orifice holes, tapered orifice pins, or various types of spring loaded valves.

Fluidic Dampers

Fluidic dampers were first produced in the 1960s, and utilize the technology of passive fluidic control. Whereas viscous shear and inertial drive dampers produce an output force that varies with velocity and (velocity)^2, respectively, fluidic orifices can be specifically designed for a wide range of damping functions. Damping functions can vary velocity exponents from as low as 0.2 to as high as 1.8, depending on customer requirements. In general, the higher the peak translational speed of the input, the lower the optimal damping exponent. Fluidic orifices operate in the 2,000–10,000 psi range, minimizing effects of fluid viscosity change, in a similar manner to an inertial fluid damper.

TESTING MACHINES FOR LARGE DAMPING DEVICES

The damping devices required for the hospital complex application noted previously have the following output parameters:

1. component type, fluidic damper;
2. maximum damping force = 330,000 lb at 60 in./s;
3. damping function, nominal: $F = 58{,}400\ V^{0.4}$, where F = damping force (lb) and V = damper velocity (in./s).

It was desired to test each damper at full force–full velocity conditions. Testing was to be performed using commercially available testing facilities, with hydraulic actuators used to drive the damper through sine wave motions, recording force, and damper stroking velocity. It quickly became apparent that no such facilities existed that could perform this test. Many laboratories had big actuators, but none had actuators that could provide large forces at high velocity. The problem was one of actuator power requirements. For example, to obtain a 330,000 lb output at 60 in./s requires a peak power of 3,000 hp. Because most hydraulic testing systems operate in the 60% efficiency range, a power source of 5,000 hp is required. A machine of this size is truly formidable in both size and cost, and was not found to be available. After extensive (and often heated) discussions, the options for testing came down to either designing and constructing an extremely large hydraulic test bench, or using another type of test concept. Because the cost of the hydraulic test bench was prohibitive, an alternate type of test was required that did not require a large and costly power source.

A decision was made to evaluate drop hammer testing, using a facility normally used to test military shock isolators at the component level, prior to shipping them to the Government for system testing. Previous military projects have exhibited excellent correlation between drop hammer testing and actual system shock tests, with the drop testing being used to establish damping constants.

DROP HAMMER TEST MACHINES

One of the easiest ways to generate large amounts of energy is to use gravity to accelerate a free falling weight. The energy input available is equal to the weight times its total falling distance,which includes the free fall distance plus the stroke of the test article. Power available is quite high, essentially limited only by the time necessary to decelerate the weight to a reduced speed.

To test 330 kips damper force at 60 in./s, the drop weight need only be raised to a height of 4.66 in. above the damper to achieve a 60 in./s contact velocity, assuming a "rigid" ground node and test fixture. During an actual test, the weight will need to be raised slightly higher to compensate for the slight deflection of the ground node and test fixture during the impact.

The effectiveness of a drop hammer is determined by its maximum throw weight, maximum shut-height, and ground node stiffness. Both commercial and Government owned drop hammers exist within the United States today, most of which were constructed for specific test applications with later use for generalized testing. By example, the drop hammer used for this project was originally built for the testing of large damping devices used on NASA's Apollo Program of the 1960s. It has an 18,000 lb weight capacity, a 44 ft shut-height, and an extremely stiff ground node frequency of 270 H, intended to simulate the primary frequency of the Apollo Launch Pad at the Kennedy Space Center. In military testing, even the most rigid engineered structures, such as the armored decks of warships, rarely exceed 75 H frequency, assuring that tests performed with this particular test rig will be conservative for an application on a commercial structure.

COMPARATIVE TEST RESULTS: DROP HAMMER VERSUS SINE WAVE ACTUATOR

The dampers utilized for testing were to be used on a base isolated structure, using elastomer isolation bearings as the spring element in the isolation system. The $V^{0.4}$ damping function was selected after extensive transient analysis had been performed to find optimum conditions of energy dissipation and building base shear loadings for the combined output of elastomer spring and damper. Important criteria that required verification by testing included:

1. variance of damping function over the expected velocity range;
2. change in damping with temperature;
3. change in damping from cycle to cycle during the maximum credible earthquake.

As noted previously, early in the design process it became evident that no available actuators existed to cycle the full sized dampers. A testing sequence evolved using drop testing on full sized devices, with both cyclic and drop testing performed on a scaled damper to demonstrate correlation between drop testing and the traditional cyclic test methods. The following is the list of tests that were performed.

1. Cyclic tests on a scaled damper using existing laboratory cyclic test equipment rated for output in the 100 kip range at speeds to 25 in./s. The scaled test damper would have output in the 50 kip range with a $V^{0.4}$ damping function and a damping coefficient set for maximum force level in the 20 in./s range.
2. Drop test the scaled damper at various drop heights, comparing force versus velocity plots from the drop test to those resulting from the cyclic tests. Agreement of drop test data points to within ±10% of the cyclic test data baseline would correlate the two test methods.
3. Perform extreme temperature tests on the scaled prototype, using a thermal box constructed around the damper on the cyclic test fixture.
4. Obtain cumulative energy data by cycling the scaled prototype rapidly until its total energy dissipated per unit volume of damping fluid equalled or exceeded the same value expected from the full sized device under the maximum credible earthquake.
5. Drop test the full sized device set for the specified 300 kips nominal output at 60 in./s using various drop heights to verify the required damping function.

The fact that the scaled damper was set to operate at a lower velocity range than the full sized device was due to limitations of the hydraulic actuator used on the cyclic test. In a fluid damper, this means only that the orifice in the device must have its total flow area adjusted by the velocity ratio of 25/60 to provide its maximum output at the reduced velocity range. When the scaled damper was designed, a degree of uncertainty existed relative to the method used to load rate the available cyclic test machine. The test machine's actuator was factory rated at 110 kips, and the machine was equipped with a pump and control valve that should allow it to achieve full actuator output at 25 in./s velocity. The uncertainty was whether the equipment manufacturer had used sinusoidal wave forms during rating tests, or a more rigorous wave form approaching that of a square wave. Driving a damper with a $V^{0.4}$ damping function through sinusoidal motion generates a force-displacement output that is basically a series of square waves, with the magnitude of the square wave varying with the peak velocity of the input wave raised to the 0.4 power. To avoid building a scaled damper that could not be satisfactorily driven by the test machine, it was decided to build the scaled damper at a 50 kip rated force, set for full output at 20 in./s. This left a suitable margin of safety to the maximum rating of the cyclic test machine.

SUMMARY OF TEST RESULTS

Figures 2–4 show cyclic test data with the expected quasisquare wave output, at a speed of 1 in./s, a sine wave frequency of 0.064 Hz, and three temperatures of 70, +120, and +32°F, respectively. For temperature testing, a thermal blanket was placed around the unit and the

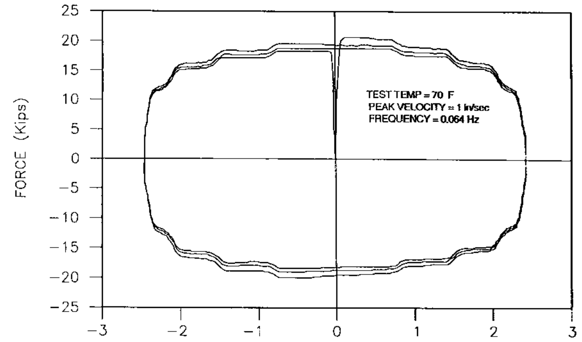

FIGURE 2 Cyclic test data, 1 in./s, 70°F.

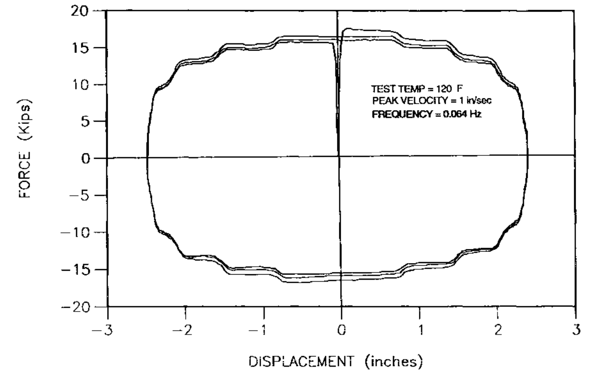

FIGURE 3 Cyclic test data, 1 in./s, 120°F.

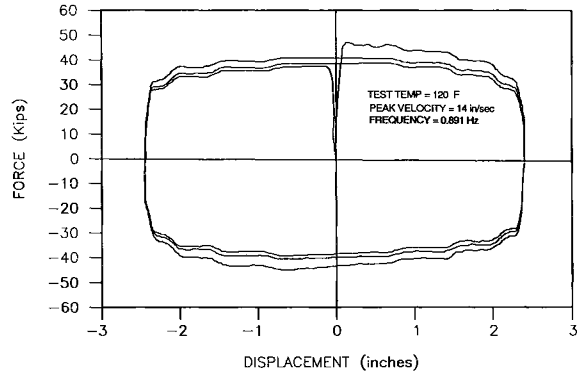

FIGURE 6 Cyclic test data, 14 in./s, 120°F.

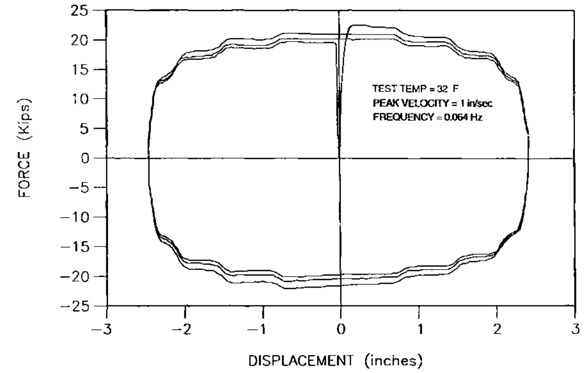

FIGURE 4 Cyclic test data, 1 in./s, 32°F.

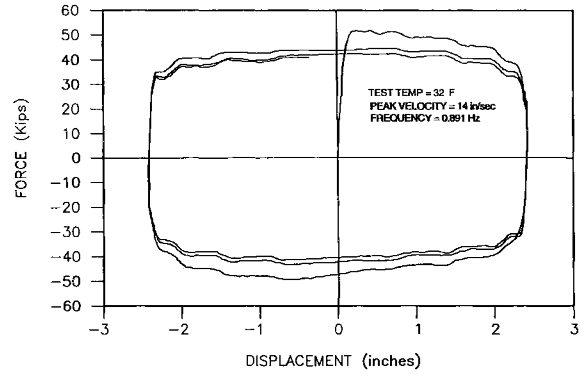

FIGURE 7 Cyclic test data, 14 in./s, 32°F.

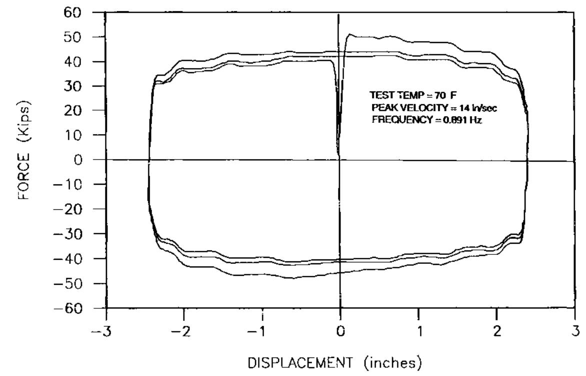

FIGURE 5 Cyclic test data, 14 in./s, 70°F.

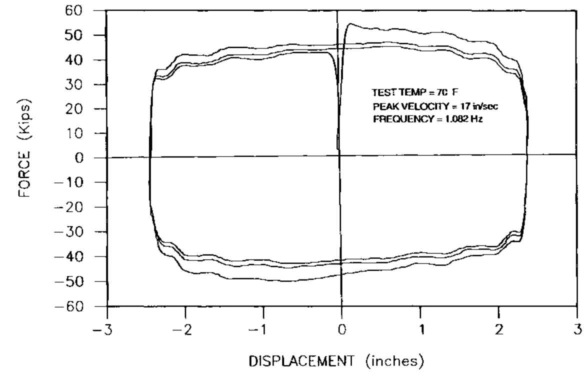

FIGURE 8 Cyclic test data, 17 in./s, 70°F.

damper was stabilized at the required temperature prior to the test.

Figures 5–7 show similar cyclic test data at a higher speed of 14 in./s, obtained by increasing the test machine frequency to 0.891 Hz, again at three temperatures. At speeds above 2 in./s, the cyclic test actuator was reaching its maximum acceleration capacity, hence, the first cycle was driven overspeed with a nonlinear command. This was necessary to obtain the specified sine wave form on the second and subsequent cycles.

Figures 8–10 show results at the maximum speed tested of 17 in./s, obtained by increasing the test machine frequency to 1.082 Hz, at the three temperatures.

Test results for cumulative energy input of the maximum credible earthquake are shown in Fig. 11, with seven complete cycles of motion at 4 in./s velocity and 0.225 Hz frequency. The cumulative energy dissipated at 3.5 cycles was equivalent in units of BTU/lb mass of fluid to that of the full scale device under the input condition of the

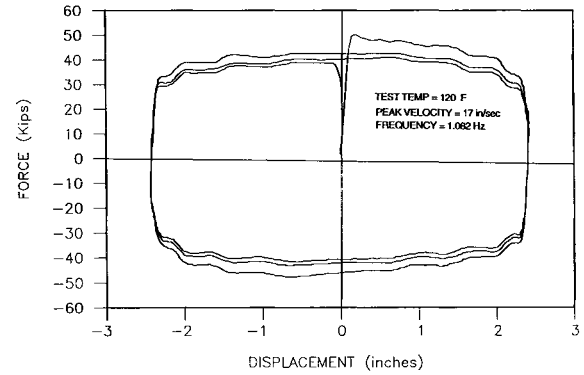

FIGURE 9 Cyclic test data, 17 in./s, 120°F.

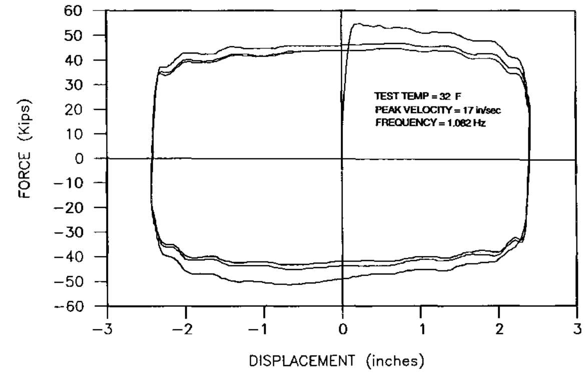

FIGURE 10 Cyclic test data, 17 in./s, 32°F.

maximum credible seismic transient for this project.

Figure 12 provides summarized thermal test results at the three temperatures selected for evaluation, these being +70, +120, and +32°F. Parameter drift for the damper was minimal over the entire range tested.

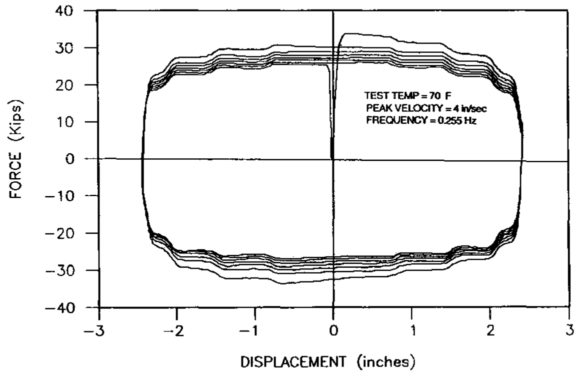

FIGURE 11 Maximum credible earthquake energy.

Figure 13 plots comparative cyclic test and drop test data on the scaled prototype damper. The 70°F cyclic test results were used as a functional baseline, with a curve fitted to the test data and an allowable correlation band width of ±10%, represented in Fig. 13 by dashed lines. All drop test points were well within the allowable bandwidth, demonstrating the comparative results from the two test methods.

Drop testing of the full sized device was successful, with no difficulties or problems noted. Figure 14 plots test results from a series of drop tests at speeds to 60 in./s and forces to the 300 kip level. All points plot within the acceptance band for the full sized device.

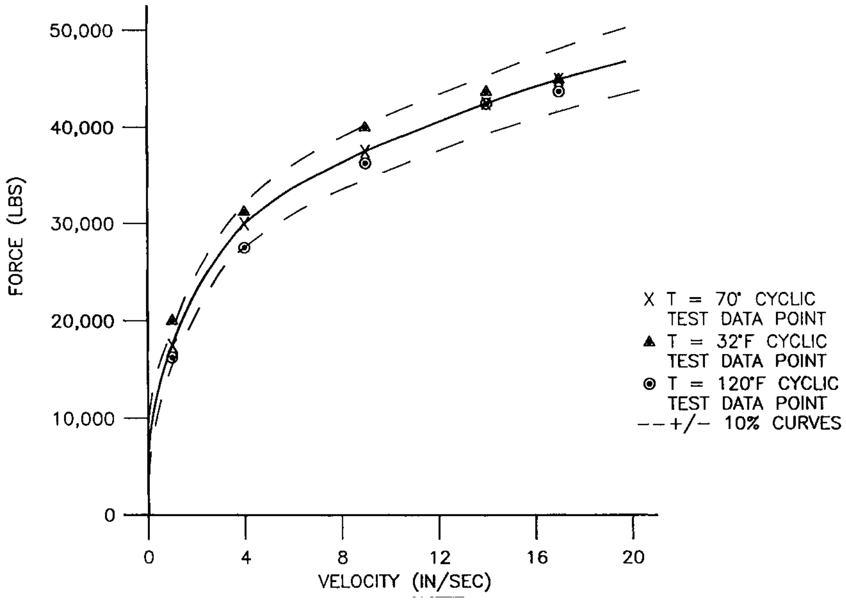

FIGURE 12 Summarized thermal test results.

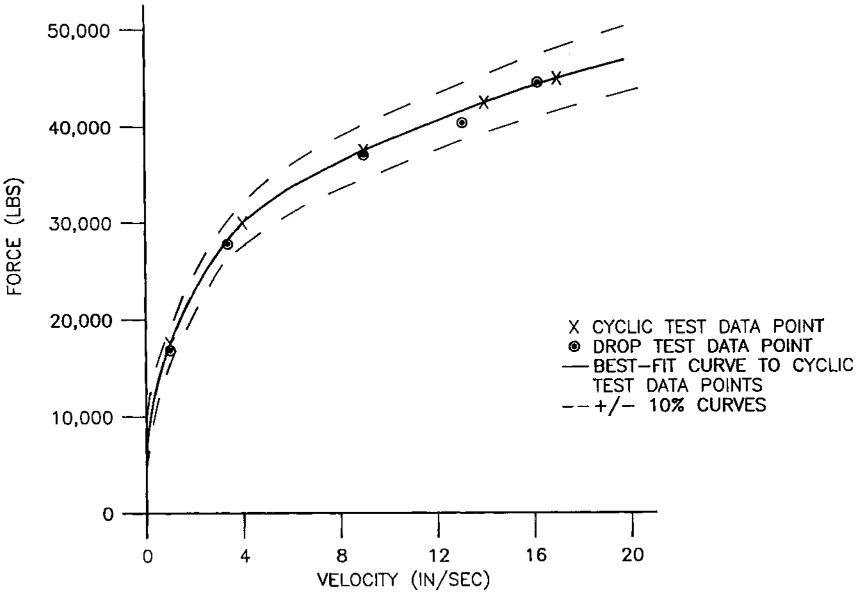

FIGURE 13 Comparative test results.

CONCLUSIONS

The use of high capacity energy dissipation devices in buildings and bridges requires that testing be performed at full scale force and velocity levels. Drop testing has been successfully proven to be an acceptable test method for large fluid damping devices. Test results demonstrate excellent correlation between drop test equipment, as used for many years by the defense community, and cyclic test equipment, as used for many years by the structural engineering community.

The use of drop testing is a cost effective way of testing full scale damping devices in the range of 100–2,000 kips output force, utilizing methods and equipment that have been proven over many years of testing and are readily available to the public at low cost.

The force and velocity ranges available from a drop test facility are limited only by the height of the drop rail and the size and strength of the seismic mass to which the rail is affixed. This allows testing of seismic damping devices to much higher speed ranges than were previously possi-

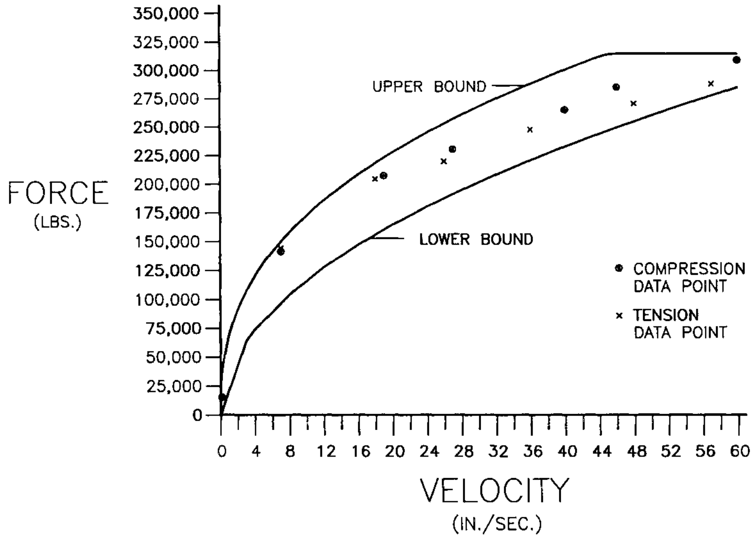

FIGURE 14 Drop test data, full size damper.

ble, allowing enhanced seismic transient requirements to be easily tested, without the need for costly development of new equipment.

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