TESTING PROCEDURES FOR HIGH OUTPUT FLUID VISCOUS DAMPERS USED IN STRUCTURES TO DISSIPATE SEISMIC ENERGY

A CASE STUDY IN DEFENSE CONVERSION

by

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Today's economic climate demands that conversion of military technology for commercial applications be a part of an aerospace and defense company's marketing plan. Towards 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 involved heavy yielding sections or sliding joints.

To incorporate this defense technology into large commercial structures required that specific test methods and procedures be developed that would be acceptable to the structural engineering community at a reasonably low cost. This paper discusses the test procedures and methodology that resulted, and provides test results from a successful application within a medical center complex in Southern California.

The fluid damper built and tested for this project has an output of 320,000 lb. force, with available displacement of 48 inches. A total of 233 pieces of this damper will be used to provide the buildings in the medical center with damping on the order of 35% of critical. The isolated buildings are designed to be free from damage at peak seismic translational velocities up to 60 inches/second.

INTRODUCTION

Taylor Devices, Inc. has manufactured damping devices for military applications since 1955. Many of our defense products have been used to protect Naval systems and components from the shock resulting from testing to MIL-S-901.

Most of the concepts, applications, and designs associated with fluid filled dampers and liquid springs for shock isolation have not been publicized, save for occasional papers presented over the years at the Shock and Vibration Symposium. However, with the end of the Cold War, and the associated budget cutbacks, it was necessary for Taylor Devices, like many other firms, to commercialize our defense technology. One of the targeted markets for our products is for use in buildings and bridge structures to attenuate the shock loadings associated with earthquakes. As with many such defense conversions, we had to endure the usual comments about "six-hundred dollar ashtrays," "cost over-runs," and "excessive overheads" which cause commercial customers to perceive defense oriented products as too costly. However, after successfully demonstrating that our technology was proven, reliable, and affordable, we were faced with a very legitimate question. This was:

"If the building and bridge constructors now have access to compact fluid isolation devices in the 100,000 lb. to 2,000,000 lb. output range, what testing methods are possible, appropriate, and most importantly, affordable?"

We successfully answered this question, and were then favored with a substantial contract for dampers to be installed into a hospital complex in southern California. Our test method was based on military shock test techniques, and is, in itself, a successful defense conversion. Figure 1 is a photograph of the full sized 330 kips output force damper.

FIGURE 1
FLUID VISCOUS DAMPER, 330 KIPS OUTPUT

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 which 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, since 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.

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 isolated base 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 to resist 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 a base isolation system. The base isolation system consists of a sliding element, such as steel slider bearings or elastomer bearings, and an energy dissipation device to provide damping.

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 which raised damping levels to the 10-15% range as a reasonable way of reducing stress within the structure. However, now that fluid damping devices have become acceptable, it is practical to increase damping to levels to the 20-40% range, offering rather dramatic stress reductions with a very compact damper design. 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-1890's. The earliest well documented use of large fluid dampers was by the military, to attenuate recoil transients on large caliber artillery pieces.

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

- 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 U.S. outdoor temperature range of -20EF to +120EF, fluid viscosity changes of ten to thirty to one are common, and this viscosity shift has a direct effect on damping forces.

- 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 change, since high inertial fluid pressures dominate the output. Inertial fluid dampers have an output force which 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 can involve complex combinations of spaced orifice holes, tapered orifice pins, or various types of spring loaded valves.

- Fluidic Dampers were first produced in the 1960's, 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. Output is generally unaffected by temperature, fluid type, and manufacturing tolerances.

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/sec.

3. Damping function, nominal:

$$F = 58{,}400\ V^{.4}$$

where F = Damping Force (lbs.) and V = Damper Velocity (in/sec.)

The project's design review committee desired to test each damper at full force-full velocity conditions, and they requested that testing be done 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 which 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/sec. requires a peak power of 3,000 horsepower. Since 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 this project came down to either creating a giant hydraulic test bench, or using another type of test concept. Since the cost of the hydraulic test bench was "not in the budget", an alternate type of test was required, which did not require a large and costly power source.

A decision was made to evaluate drop hammer testing, using the same facility used by Taylor Devices to test its military shock isolators at the component level, prior to shipping them to the Government for system testing. Nearly all of our military projects have exhibited excellent correlation between drop hammer testing and actual full scale 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 the 330 kip damper at 60 in/sec., the drop weight need only be raised to a height of 4.66 inches above the damper to achieve a 60 in/sec. 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 U.S. today, most of which were constructed for specific test applications with later use for generalized testing. The drop hammer used for this project is owned by Taylor Devices, and was originally built for the testing of large damping devices used on NASA's Apollo Program of the 1960's. It has an 18,000 lb. weight capacity, a 44 ft. shut-height, and an extremely stiff ground node frequency of 270 hertz, intended to simulate the primary frequency of the Apollo Launch Pad at the Kennedy Space Center. In our military testing, even the most rigid engineered structures, such as the armored decks of warships, rarely exceed 75 hertz frequency, assuring that tests performed with this particular test rig will be conservative.

COMPARATIVE TEST RESULTS: DROP HAMMER VS. SINE WAVE ACTUATOR

For this project, the building owner had purchased a quantity of the 330 kip dampers discussed previously. The dampers were to be used on a base isolated structure, using elastomer isolation bearings as the spring element in the isolation system. The $V^{.4}$ 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.

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. Perform tests with a scaled damper using existing laboratory cyclic test equipment rated for output in the 100 kip range at speeds to 25 in/sec. The scaled test damper would have output in the 50 kip range with a $V^{.4}$ damping function and a damping coefficient set for maximum force level in the 20 in/sec. range.

2. Drop test the scaled damper at various drop heights, comparing force vs. velocity plots from the drop test to those resulting from the cyclic tests. Agreement of drop test data points to within plus or minus 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 equaled 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 kip output at 60 in/sec. 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 which should allow it to achieve full actuator output at 25 in/sec. 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 $V^{.4}$ 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/sec. This left a suitable margin of safety to the maximum rating of the cyclic test machine.

SUMMARY OF TEST RESULTS

Figure 2 shows cyclic test data with the expected quasi-square wave output, at a speed of 1 in/sec., a sine wave frequency of .064 Hz., and three temperatures of 70EF, +120EF, and +32EF. For temperature testing, a thermal blanket was placed around the unit and the damper was stabilized at the required temperature prior to test.

Figure 3 shows similar cyclic test data at a higher speed of 17 in/sec., obtained by increasing the test machine frequency to 1.082 Hz., at three temperatures. At speeds above 2 in/sec., the cyclic test actuator was reaching its maximum acceleration capacity, hence, the first cycle was driven overspeed with a non-linear command. This was necessary to obtain the specified sine wave form on the second and subsequent cycles.

Test results for cumulative energy input of the maximum credible earthquake is shown in Figure 4, with seven complete cycles of motion at 4 in/sec. velocity and .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 maximum credible seismic transient for this project.

Figure 5 provides summarized thermal test results at the 3 temperatures selected for evaluation, these being +32EF, +70EF, and +120EF. Parameter drift for the damper was minimal over the entire range tested.

Figure 6 plots comparative cyclic test and drop test data on the scaled prototype damper. The 70EF cyclic test results were used as a functional baseline, with a curve fitted to the test data and an allowable correlation band width of plus or minus 10%, represented in Figure 6 by dashed lines. All drop test points were well within the allowable band width, demonstrating the comparative results from the two test methods.

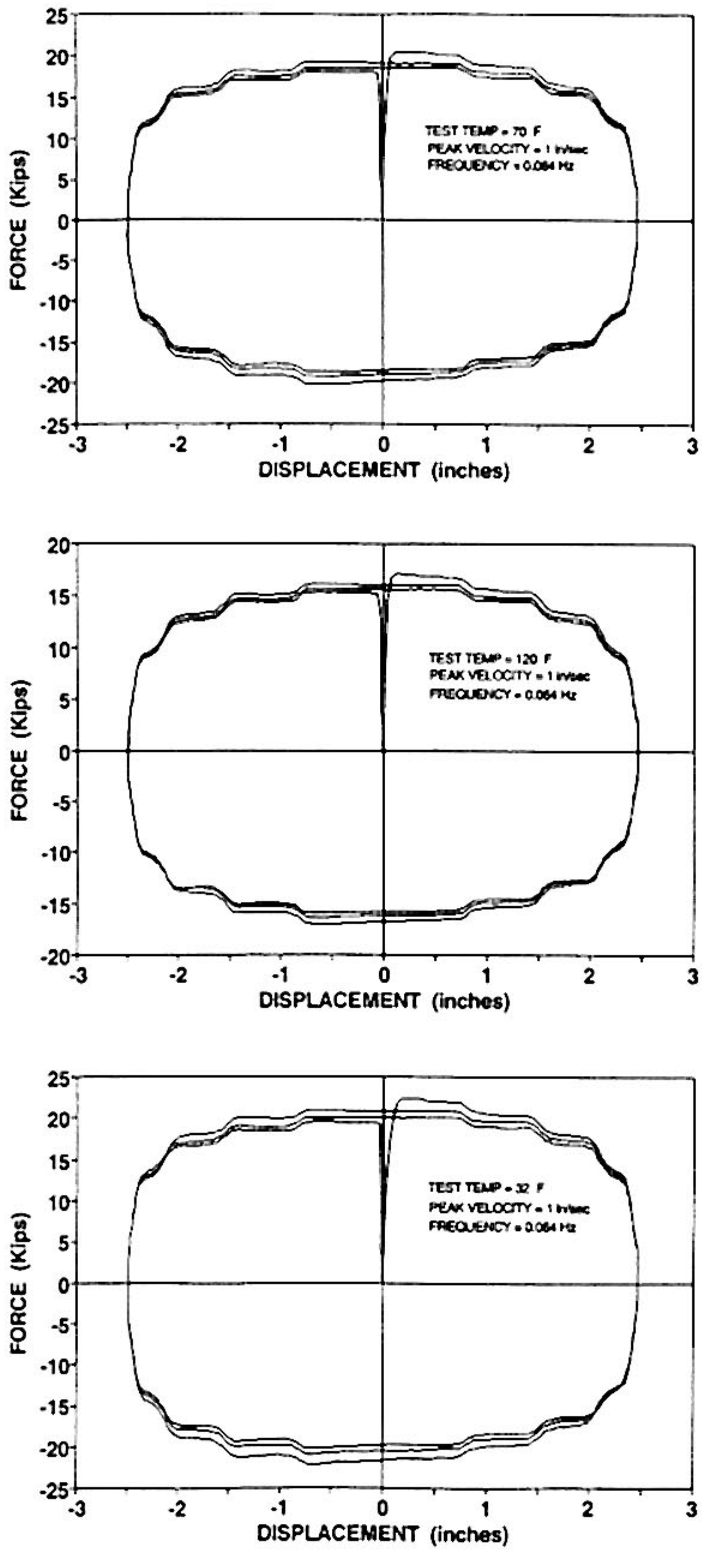
Drop testing of the full sized device was equally successful, with no difficulties or problems noted. Figure 7 depicts test results from a series of drop tests at speeds to 60 in/sec. and forces to the 300 kip level. All points plot within the acceptance band for the full sized device.

CONCLUSION

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 now 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 kips to 2000 kips output force, utilizing methods and equipment that have been proven over many years of testing and which 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 the rail is affixed to. This allows testing of damping devices to much higher speed ranges than were previously possible, allowing enhanced seismic transient requirements to be easily tested, without the need for costly development of new equipment.

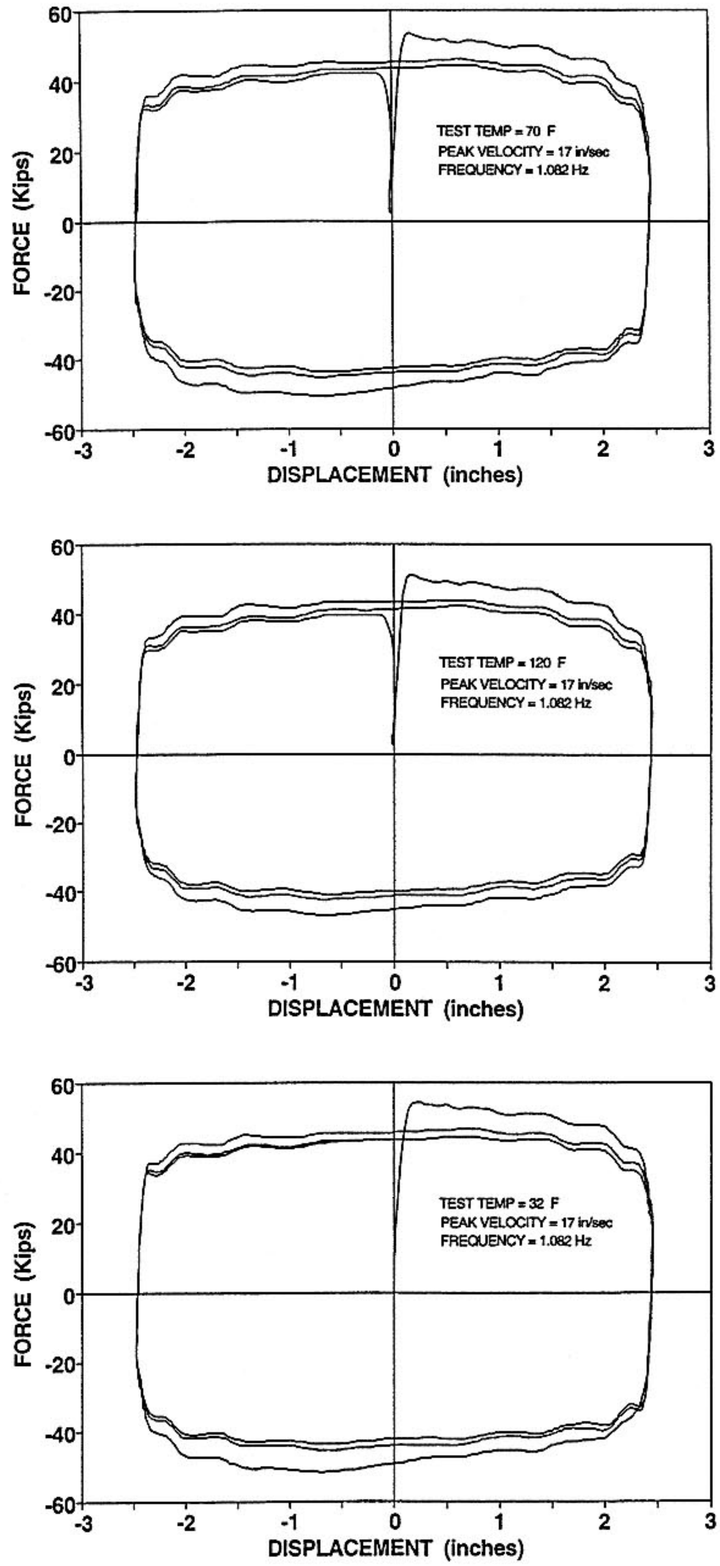


+ 70°F

+ 120°F

+ 32°F

FIGURE 2
CYCLIC TEST DATA, 1 IN/SEC., 3 TEMPERATURES



+70°F

+120°F

+32°F

FIGURE 3
CYCLIC TEST DATA, 17 IN/SEC., 3 TEMPERATURES

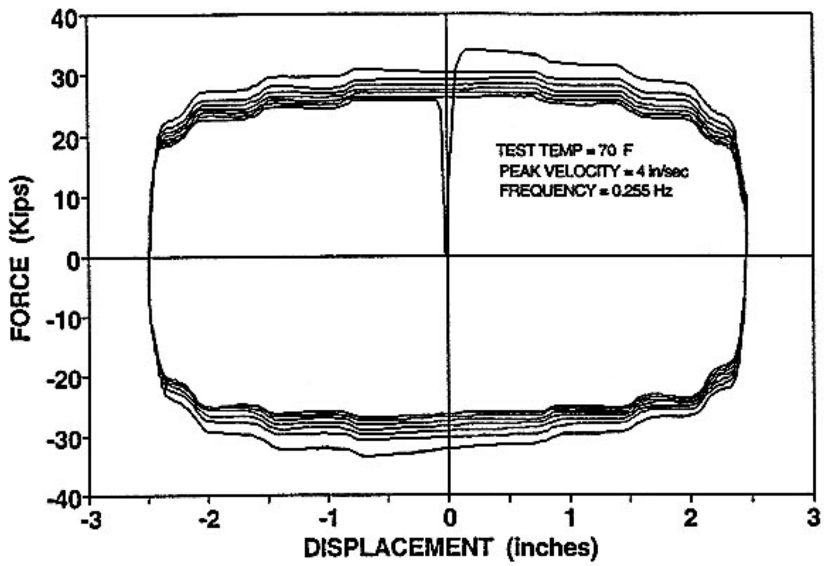


FIGURE 4
MAXIMUM CREDIBLE EARTHQUAKE ENERGY

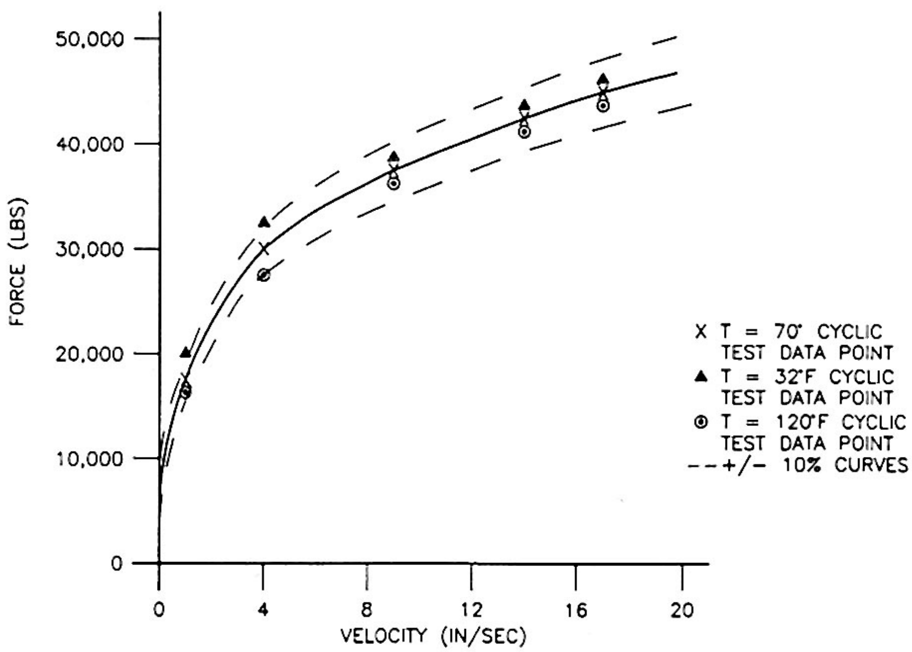


FIGURE 5
SUMMARIZED THERMAL TEST RESULTS

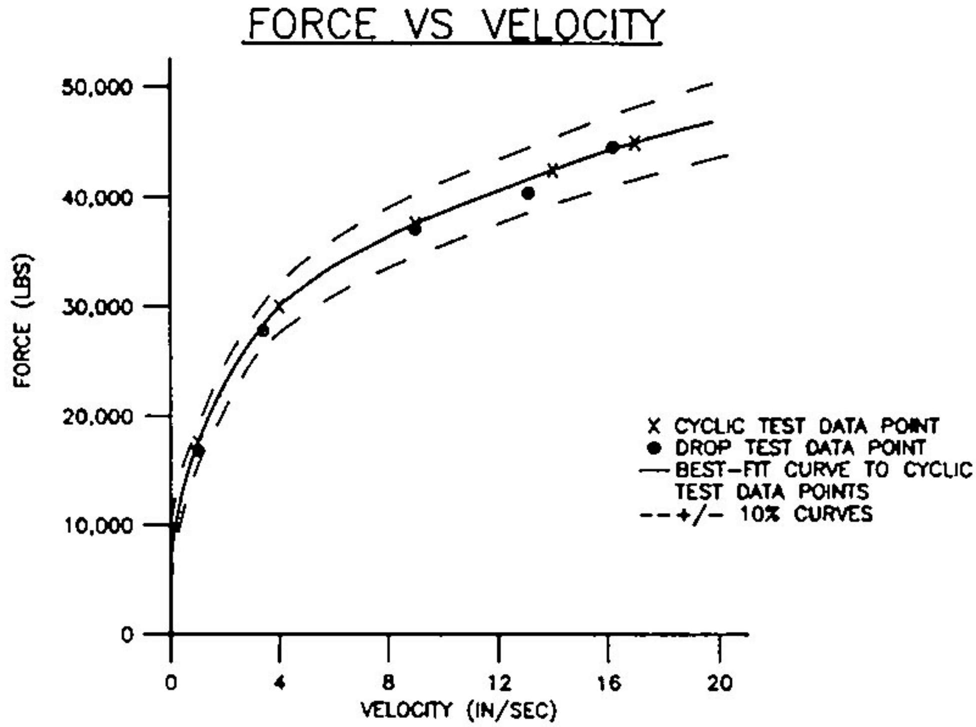


FIGURE 6

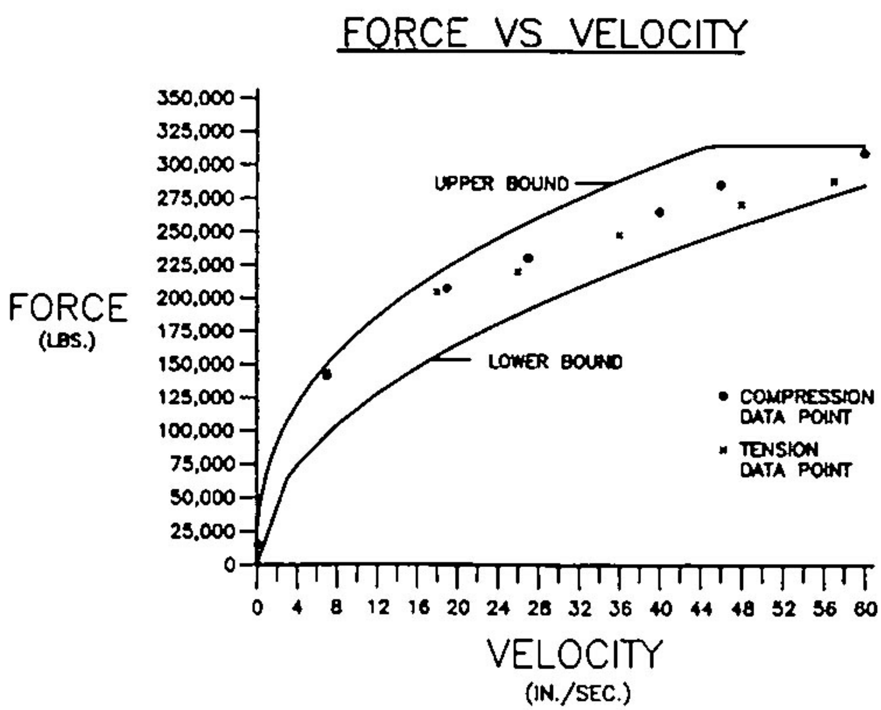


FIGURE 7