PRE-QUALIFICATION TESTING OF VISCOUS DAMPERS FOR THE GOLDEN GATE BRIDGE SEISMIC REHABILITATION PROJECT

A report to T.Y. Lin International, Inc.
and the Golden Gate Bridge District

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This testing program would not have been possible without the significant contributions of a number of people. Drs. Amir Gilani and Changrui Yin were instrumental in the design and fabrication of the damper test machine, and Dr. Gilani's involvement continued throughout the course of the testing program. The significant daily efforts of Mr. Wesley Neighbour and the technical expertise and contribution of Mr. Don Clyde of the EERC are also acknowledged. All four manufacturers are recognized for their willing cooperation throughout the testing program.

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1. INTRODUCTION

1.1 Project Description

This report presents the results of the testing of one viscous damping device provided to the Earthquake Engineering Research Center (EERC) of the University of California at Berkeley for pre-qualification testing as part of the seismic rehabilitation of the Golden Gate Bridge. In all, four different viscous dampers from four different manufacturers were tested in the pre-qualification program. This report presents the test results for the damper denoted *Damper C*. The test results for the other three dampers, *Dampers A, B, and D,* are presented in separate reports.

All of the viscous dampers in the testing/pre-qualification program are significantly smaller than the dampers intended for use in the seismic rehabilitation of the Golden Gate Bridge. Dynamic cyclic testing of the full-size dampers over a useful range of velocity and displacement is currently beyond the capability of existing test machines. Therefore, a reduced-scale (model) damper design was developed to permit dynamic cyclic testing of the model, and to provide meaningful results by which both the model and full-size damper behavior could be evaluated. The parameters of the model damper design were selected on the basis of the capacity of the hydraulic pumping system of the Earthquake Simulator Laboratory of the EERC. Details of the model damper design for the testing/pre-qualification program are given in Chapter 3.

This report presents the results of the testing program and evaluates the results in terms of the requirements established in the test specification. No pass-fail evaluation of Damper C is made; this will be made by the Damper Evaluation Panel that has been established by T. Y. Lin International (TYLI).

The specification for the testing of the viscous dampers was developed by TYLI, and details of the execution of the testing program were developed jointly by TYLI and the EERC. All four dampers were subjected to the same testing program.

The testing/pre-qualification program was funded by the Golden Gate Bridge and Transportation District through TYLI.

1.2 Organization of this Report

The scope of this report is the presentation of the results of the pre-qualification testing of one of four viscous damping devices, Damper C, as part of the seismic rehabilitation of the Golden Gate Bridge. Three companion reports describe the testing of the other three viscous dampers.

This report is organized into six chapters and four appendices. Chapter 2 describes the damper test machine designed and fabricated specifically for the testing/pre-qualification program, the overall test set-up including instrumentation and temperature control equipment, and the control and data acquisition system. Chapter 3 presents a brief description of Damper C. Chapter 4 describes the details and objectives of the testing/pre-qualification program, and Chapter 5 presents the test results and discussion of the results in the context of the test specification requirements. Chapter 6 summarizes the results of the testing program.

The appendices provide supplemental details. Appendix A presents graphical results for all of the cyclic tests performed on the damper. Appendix B presents results and evaluation of the sinusoidal/energy dissipation tests. Appendices C and D present the *Testing/Pre-Qualification Program for Model Dampers* and the *Technical Requirements for Full-Size Dampers*, respectively.

2. DESCRIPTION OF TEST MACHINE

2.1 General

The test machine used for the viscous damper testing/pre-qualification program was designed and fabricated specifically for this project. It was designed to enable cyclic dynamic testing and sustained endurance testing of uni-axial viscous damping devices under a range of temperature conditions. The machine tests dampers in a vertical orientation. The machine was designed at the EERC and fabricated by RBJ Fabricators and G&W Machining, both of Richmond, California. A schematic view of the damper test machine is shown in Figure 1.

The force, velocity, and displacement capacities for the test machine were selected on the basis of the capacity of the hydraulic pumping system of the EERC Earthquake Simulator Laboratory. The machine has a stroke of ±6 in., with a maximum force output of approximately 120 kips at 3000 psi, and a maximum loading velocity of approximately 20 in./sec.

2.2 Detailed Description

The test machine uses two Shaeffer 60-kip double-acting hydraulic jacks to apply load to the test specimen. The jacks are arranged in parallel and are connected at their bases to braced jack stands and at their rod ends to a loading beam that also connects to the test damper, positioned mid-way between the jacks. The jacks are mounted with Moog Controls 200 gpm servo-valves and manifolds. The jacks are controlled via ±10 in. Trans-Tek AC Linear Variable Differential Transformers (LVDTs) that are mounted at the bottom end of the jack piston rods inside the jack stands.

The test specimen is connected to clevices by 2.5-in. diameter pins at the base of the machine and to the mid-span of the loading beam. A force transducer to directly measure damper force is included in-line with the damper at the top clevice bracket. The jack-to-loading beam connections consist of two different details. At the end of one jack piston rod a clevice is used, while at the end of the other a spherical bearing is attached to a transverse rod on the loading beam. This arrangement accommodates any unexpected unequal or out-of-phase movement of the two jacks without damage to the test machine.

The four dampers tested varied in size and length. The different damper lengths were accommodated by the use of spacer pedestals, unique to each damper, that permitted the appropriate positioning of each damper in the test machine. The different damper sizes also required the use of different temperature chambers for the heating/cooling system.

For some tests, a lateral load was applied to the damper to simulate gravity load. This was achieved through a simple pulley and hanging weight arrangement. It was not possible, however, to have both the temperature chamber and the lateral loading system in place at the same time. Thus, all of the tests of the damper with a lateral load applied were performed under laboratory ambient temperature conditions only.

The test machine and data acquisition system are run by a PC Windows-based control and acquisition program called ATS, or Automated Testing System, developed by the SHRP Equipment Corporation of Walnut Creek, California. The program is capable of signal generation, four-channel servo-actuator command, and 16-channel data acquisition. (For most of the tests performed in the viscous damper testing/pre-qualification program ATS was not used for signal generation; rather, separately written ASCII command signals were used by ATS to control the test machine).

2.3 Temperature Control System

A simple temperature control system was developed to permit testing of the viscous dampers over a wide range of elevated and reduced temperatures. A view of the temperature control chamber in place around a damper in the test machine is shown in Figure 2. Plywood boxes were constructed so that each damper could be entirely enclosed while in the test machine. The front panel of each box consisted of a sheet of Lexan to permit viewing of the damper during testing. The box was entirely lined with foam and foil insulation panels, and rubber gaskets were used to seal around the top end of the damper that projected out of the temperature box.

The heating system consisted of multiple lengths of industrial-grade heating tape draped inside the box, with a total heating capacity of approximately 2 kW. The cooling system utilized liquid nitrogen supplied from a 50-gallon cylinder and regulated by a cryogenic solenoid valve (Figure 3). Circulation fans were used inside the chamber to ensure near uniform temperature distribution. The chamber temperature was regulated by a two-channel control system connected to the heating and cooling circuits. The controller permitted straightforward changes in damper temperature over the required range for testing at 40 °F to 125 °F. A thermocouple placed at mid-height inside the temperature chamber was used for temperature control feedback. The damper external surface temperature was measured in three locations, as described in the following section.

2.4 Instrumentation

The primary instrumentation consisted of an Eaton LeBow 150-kip fatigue-rated force transducer mounted in-line with the damper to record damper force output, and a wire potentiometer mounted on the damper to measure damper displacement (i.e., providing a direct measurement of the relative displacement of the rod with respect to the main body of the damper). Measurement of the damper displacement in this way eliminated any tolerance looseness present in the end bearing-clevice pin connection, and provided the best possible displacement from which to evaluate the damper behavior. The displacement signals from the two jack control LVDTs were recorded in all of the tests.

The external surface temperature of the damper was measured by thermocouples in three locations. Because of the design of Damper C, it was not possible to place the thermocouples at the desired top-, mid-, and bottom-stroke positions. A description of the thermocouple placement is given in Section 5.1. For those tests in which the damper was enclosed in the temperature chamber, three thermocouples were used to record the temperature within the chamber, at the bottom, mid-height and top of the chamber. The feedback thermocouple temperature was also recorded. For the tests in which the damper was not enclosed in the temperature chamber, a single thermocouple was used to monitor the laboratory ambient temperature near the damper.

3. DESCRIPTION OF TEST DAMPER

3.1 Full-Size and Model/Test Damper Performance Requirements

T. Y. Lin International (TYLI) has determined that dampers with a constitutive law of

$$F = 75 \cdot V^{0.5} \quad \text{kips} \qquad \text{Eq. 3.1}$$

are required for the seismic upgrade of the Golden Gate Bridge. These dampers will be required to have a maximum stroke of about 50 in., and be able to sustain a peak velocity of 75 in./sec. (see Appendix D for more details). At 75 in./sec., the dampers will produce a force of approximately 650 kips. The average power output of one damper under earthquake loading conditions will be about 350 horsepower (261 kW), with a peak power output of about 7250 horsepower (5.41 MW).

These quantities are well beyond the capacity of any existing seismic testing laboratory. In order to obtain a damper design that would prove practical for a cyclic dynamic testing/pre-qualification program, the full-size damper design was scaled down. The model damper design selected required that the damper be capable of ±6 in. displacement, that it have a constitutive law of

$$F = 22.4 \cdot V^{0.5} \quad \text{kips} \qquad \text{Eq. 3.2}$$

and be capable of producing 100 kips force under a maximum test velocity of 20 in./sec.

The parameters selected for the model damper, therefore, represent scale factors of approximately 1:6.5 for force, 1:4 for displacement, and 1:3.75 for velocity.

3.2 Description of *Damper C*

The viscous damping device denoted *Damper C* is shown in Figure 4. The damper is shown in its fully compressed position in the figure. It is a uni-axial viscous fluid damper, with a maximum cross-sectional dimension of approximately 13 inches and a length of 68.1 in. (measured to the center-line of the end bearings) in its mid-stroke undeformed position. The damper has a total stroke of ±8.0 in. The damper end connections consist of spherical bearings that accept a 3.0-in. diameter pin. These were sleeved, with a bushing provided by the manufacturer, to accept the 2.5-in. diameter clevice pins on the test machine. The largest diameter portion of the damper, the outer sleeve, serves two purposes. It acts to protect the piston rod and seals at the point of exit from the main cylinder, and it also provides lateral rigidity to the damper via a Delrin sealing ring that contacts the main cylinder (with reference to Figure 4, this seal is at the right end of the largest diameter section of the damper, near the indicated location of the middle thermocouple).

Viscous dampers for the testing/pre-qualification program were required to meet the half-power law of Eq. 3.2, or some other law offered by the manufacturer, so long as it was validated by TYLI prior to the testing program. Damper C was designed to meet the constitutive law stated in Eq. 3.2.

4. DAMPER TEST PROGRAM

4.1 Test Program Objectives

The primary objectives of the testing/pre-qualification program for the model dampers were to:

- Evaluate the performance of the dampers under a range of cyclic constant-velocity loading conditions to verify their constitutive relationships;
- Evaluate the damper constitutive relationships under a wide range of temperature, cyclic displacement amplitude, and frequency;
- Evaluate the energy dissipation capability of the dampers under sinusoidal displacement loading;
- Subject the dampers to a very large number of large-amplitude, low-velocity cycles to evaluate the wear characteristics of the seals; and
- Subject the dampers to a Maximum Credible Earthquake (MCE) displacement loading determined from TYLI's design analyses.

4.2 Detailed Description

The complete test program developed to meet the objectives described above is presented in Table 1. The following sections describe in detail the different types of tests performed and the related performance criteria for each type of test.

Appendix C presents the *Testing/Pre-Qualification Program for Model Dampers* document developed by TYLI. This document gives the general requirements and conditions of the testing/pre-qualification program, the performance and scaling requirements for the model dampers, a general description of the testing program, and the performance evaluation criteria for the different types of tests.

The test program presented in Table 1 is divided into four main sections: A. Initial Cyclic Tests; B. Endurance/Seal Wear Test; C. Cyclic Tests; and D. Seismic Displacement Input Test. The table gives the main characteristics of each test, including the test velocity, amplitude, frequency, number of cycles, theoretical peak force developed in the damper, theoretical total energy input, (nominal) test temperature, and a description of the test type.

Test Groups

The entire test program constituted an enormous total energy input to Damper C, approximately 21 times the energy corresponding to the Maximum Credible Earthquake (MCE) computed by TYLI. As such, care was required in the execution of the test program to ensure that tests performed in close succession did not excessively over-heat the damper. To that end, the test program was divided into groups of tests (A, B, C, D, etc., see Table 1). One test group was performed at a time, and then the damper was allowed to cool before performing the subsequent test group. The maximum short-term energy dissipation demand on the dampers occurs in the MCE (about 10,000 kip-in. for the model dampers), and this value was used to arrange the tests into groups. In a few cases, however, it was not possible to limit the total energy in a test group to this value (especially in the case of the 10-cycle, ±6 -in., 20 in./sec. sinusoidal energy dissipation test) and this fact should be recognized as an indication of the severity of the test program.

Temperature Conditioning

For the tests performed at a specified temperature, the dampers were soaked/pre-conditioned for at least 12 (but typically 14 - 16) hours before the start of testing at that temperature. All of the tests in a single group were performed in succession, with a five-minute break between individual tests. The damper was allowed to cool between test groups. Cooling was typically permitted for about 2 - 4 hours, or until the damper external temperature appeared to stabilize "close" to the nominal testing temperature. Obviously it was not practical to permit the damper to re-attain equilibrium at the nominal test temperature - this would have required many hours between each test - so, to expedite the testing program, the temperature control system was often used to "pull down" the damper temperature to close to the nominal test temperature between each group of tests. This method meant that test groups could be performed about every two hours.

4.2.1 Constant-Velocity Cyclic Tests

Most of the testing program consisted of constant-velocity cyclic tests performed for a range of velocity, amplitude, and temperature. The applied velocity varied from 1 to 20 in./sec. (actually, 1, 2, 5, 10, 15, and 20 in./sec. nominal) with amplitudes of ±0.6 , 1, 3, and 6 in. and temperatures of 40 °F, 70 °F, and 125 °F.

The very first tests of the damper consisted of a series of *initial cyclic tests* (tests I.1 - I.10 in Table 1), performed at 70 °F, and intended to provide a characterization of the damper behavior prior to the endurance test. The *endurance test* (test W.1 in Table 1) was then performed, followed by the same set of cyclic tests again. This approach was chosen so that the two sets of cyclic tests could be compared to evaluate any change in damper behavior due to the large number of loading cycles in the endurance test. Additional constant-velocity tests were also performed at 70 °F, and then a selected series of tests were repeated at both 125 °F (tests C.15 to C.24) and 40 °F (tests C.25 to C.34). The results of these three sets of tests were then compared to reveal any change in damper behavior due to temperature.

The testing specification requirement for the constant-velocity tests is that:

The force-velocity response matches the constitutive law prediction within ±15 percent, for strokes greater than 10 percent of full stroke, over the full range of frequency, and at 40 °F, 70 °F, and 125 °F, for all test cycles.

In the case of Damper C, the constitutive law prediction is that given in Eq. 3.2.

4.2.2 Endurance/Seal Wear Test

This test was intended to be an endurance/wear test of the dampers' sealing systems. The test consisted of 1800 cycles of loading at a constant velocity of 0.5 in./sec. and an amplitude of ±6 in. The test was performed without the temperature control chamber in place around the damper, and with a lateral load applied to the damper to simulate gravity loading. A view of Damper C in the test machine with the lateral load applied is shown in Figure 5. The specific value of lateral load was required to be equal to the ratio of bearing area between the model and the full-size damper times the anticipated weight of the full-size damper. The manufacturers were required to state the lateral load to be applied to the model dampers. For Damper C this load was 890 lb. The endurance test had a total duration of 24 hours, and took 3-4 days to complete. The test was performed in subsets of 150 cycles, which each took two hours to complete. At the end of each 150 cycles, the data was downloaded and checked before the subsequent set was performed. Response data was not recorded continuously throughout the endurance test. Instead, data was typically acquired for the first and last five (or ten) cycles of a 150-cycle subset, and for every tenth cycle in between.

The testing specification requirement for the endurance/seal wear test is as follows:

The dampers will be considered to have passed the test if there is no observed (or very small) fluid loss and no evidence of seal degradation. The dampers will not be taken apart to inspect the seals, however.

4.2.3 Sinusoidal/Energy Dissipation Tests

In addition to the constant-velocity cyclic tests, a number of sinusoidal displacement tests were performed to evaluate the energy dissipation capability of the damper. The sinusoidal tests were at amplitudes of 2, 4, and 6 in., and peak velocities of 5, 10, and 20 in./sec. All of the sinusoidal tests but one consisted of five cycles of loading. The exception was a 10-cycle test of 6 in. amplitude and peak velocity of 20 in./sec. This test input approximately two times the MCE-equivalent total energy to the damper (about 21,000 kip-in.) and was intended to be an energy dissipation and endurance test. The specification acceptance criteria were applied to the first five cycles of this test; no acceptance criteria were applied to the remaining cycles of the test.

The matrix of sinusoidal tests was divided into three sets, with tests performed at each of the three test temperatures of 40 °F, 75 °F, and 125 °F.

The testing specification requirement for the sinusoidal/energy dissipation tests is as follows:

The force developed by the dampers is primarily dissipative. The area of the damper force-displacement hysteresis loops shall be at least 82.5 percent of the rectangular area defined by the peak force and peak displacement, for strokes greater than 25 percent of full stroke, over the full range of frequency, and at 40 °F, 70 °F, and 125 °F (with each cycle considered independently).

4.2.4 Earthquake Input

The final test of the dampers consisted of a Maximum Credible Earthquake (MCE) displacement input scaled from TYLI's global analysis of the Golden Gate Bridge. This analysis was performed for each of the four dampers; in the case of Damper C, the analysis was performed assuming a 0.5-power constitutive law for the dampers. The characteristics of the earthquake input loading for Damper C are shown in Figure 6.

The testing specification includes no performance requirement for the earthquake input test. ?

4.2.5 Friction Test

A very slow one-directional force-control test was performed to evaluate the friction resistance of the damper. This test involved loading the damper monotonically at a rate of one kip/minute until the damper piston rod began to move. The test was performed in both tension and compression directions at temperatures of 40 °F, 70 °F, and 125 °F. As Damper C was tested in the vertical position, with the piston rod downward, an additional friction test was also performed. This simply involved disconnecting the damper from the top load beam and observing whether or not any downward movement of the damper occurred. If movement was observed, it indicated that the damper frictional resistance was less than the weight of the damper (minus the weight of the piston rod and piston).

The testing specification required that the damper friction force not exceed 2 1/2 percent of the damper capacity (100 kips), i.e., 2.5 kips.

5. TEST RESULTS

5.1 General

This section presents the results of the testing/pre-qualification program. The main aspects of the results are presented and discussed, and the results are also compared with the test specification acceptance criteria.

The design of Damper C did not permit easy placement of thermocouples in the preferred locations on the outside of the damper. Three thermocouples were attached directly to the main body of the damper, and their locations are indicated in Figure 4. The left (bottom stroke) thermocouple was attached to the outer sleeve, which meant that it was significantly remote from the main cylinder. The mid- and top-stroke thermocouples were attached to the main cylinder. Because the main cylinder surface slides on a seal (on the inside edge of the outer sleeve), the mid-stroke thermocouple position was adjusted by about 2 in. to avoid contact with the seal.

The tests of Damper C were thoroughly documented with written observations and photographs where appropriate. A number of tests were also recorded on video. These included some constant-velocity tests, sinusoidal tests, and the earthquake input test.

The complete set of tests performed on Damper C is listed in Table 2. The results from these tests are presented and discussed in the following sections. Appendix A presents plots of all of the cyclic tests performed on Damper C.

5.2 Constant-Velocity Cyclic Tests

Typical results from the constant-velocity cyclic tests are presented in Appendix A. Three plots are shown for each test as follows: a damper force-displacement plot; the time history of the damper velocity; and time histories of damper (denoted "pot" for wire potentiometer) displacement and the average of the two jack displacements. Typically the damper and jack displacements were not the same, due to tolerances and losses in the clevice connections to the damper and the connections between the jack piston rods and the loading beam.

Calculation of Damper Force and Velocity from Test Results

The results of the constant-velocity cyclic tests shown in Figures 7 and 8 plot a single point of force versus velocity for each test. The values plotted are determined using the following approach. The damper velocity was first obtained by differentiation (with some smoothing) of the damper displacement. The velocity versus time plot for a constant-velocity test is an approximately regular square wave (for example, see the first plot in Appendix A for test *sawi1*, file *950504.01*). The horizontal lines plotted in the figure are at plus and minus 1 in./sec., the target velocity for the test. For each half cycle of loading (11 in total) a single velocity point was selected that was either closest to or at the target velocity. (Note that in the case of the higher velocity tests, the target velocity was not always reached, and in these cases a velocity point closest to the target velocity was chosen. In some of the highest velocity tests, the first half cycle was significantly below the target velocity; in those cases that cycle was ignored). The time-coincident damper force was then identified for the (up to) 11 points of velocity. The set of velocity and corresponding force values were finally averaged. A single point of force-velocity in Figure 7 or 8, therefore, is the mean value pair of force-velocity for a test.

5.2.1 Initial Cyclic Tests

The force-velocity values determined from the initial cyclic tests are shown in Figure 7, indicated by the points labeled "before." The results of the same tests repeated immediately after the endurance test are shown in the same figure by the points labeled "after." Both sets of tests were performed at a nominal temperature of 70 °F. The solid line in the figure is the $F = 22.4 \cdot V^{0.5}$ target constitutive law for Damper C, and the upper and lower dashed lines plot the ± 15 percent range, respectively, permitted by the testing specification. It can be seen that, for all of the tests, the damper performed within the specification range, with force values slightly above the target law for low velocities and slightly below the target law for high velocities. This result suggests that the damper actually has a velocity exponent slightly less than the target value of 0.5. There is no indication from the plotted results that the endurance test affected the behavior of the damper in any way.

5.2.2 Post-Endurance Cyclic Tests

Figure 8 presents the results for all of the constant-velocity cyclic tests performed at the three nominal temperatures of 40 °F, 70 °F, and 125 °F. The results are indicated according to temperature in the figure.

(In addition to the tests for which results are presented in the figure, a number of additional tests were performed on Damper C. After a few of the 125 °F tests had been performed, it became apparent that the damper temperature was not being kept uniform by the temperature chamber. The chamber was modified and the 125 °F friction tests and five dynamic tests were repeated. The results presented in Figures 8 - 10 include only the repeated tests).

At 1, 2, and 5 in./sec., there is a trend that the damper force at a given velocity is highest in the 40 °F tests and lowest in the 125 °F tests; there is no similar trend, however, for the 10, 15, and 20 in./sec. tests.

Figure 9 presents the results for all of the constant-velocity tests in terms of test amplitude, and Figure 10 presents the same results in terms of test velocity. Figure 9 does not appear to indicate that test amplitude has any effect on the force-velocity behavior of the damper. Similarly, Figure 10 does not indicate that test frequency has any effect on the force-velocity behavior of the damper. The results in Figures 8 - 10 show that the damper performs within the allowable range for all of the tests.

In addition to the force-velocity results in terms of amplitude and frequency in Figures 9 and 10, the results from three tests are examined in more detail in Figure 11. The figure plots points of force-velocity for each half cycle of tests I.7, I.8, and I.10 (a total of nine points for each test, disregarding the first and last half-cycle values). This figure indicates the variation of the damper force-velocity behavior over the five test cycles. The highest force value at a given velocity corresponds to the first test cycle, and as the test progresses and the number of cycles increases, the force gradually drops.

Figure 12a shows the behavior of the damper in test I.10 (±3 in. amplitude, 15 in./sec. constant velocity, 5 cycles) in more detail. The recorded damper force output in the test is plotted, along with the upper and lower specification ranges determined using the target force-velocity law and the actual test velocity. It can be seen from the figure that the damper force at the start of the test is close to (and actually at one point exceeds) the maximum allowable force. As the test progresses, the damper force output drops, to near the minimum of the allowable range at the end of the test. This indicates that the damper behavior is somewhat affected by the transient temperature increase during dynamic loading. Figure 12b provides more detail of this behavior, where the same information as Figure 12a is plotted, but for test D.2 (±6 in. amplitude, 20 in./sec. peak velocity sinusoidal, 10 cycles). It can be seen that the damper force output drops over the first four cycles (after slightly exceeding the maximum allowable force in the first two half cycles), but for subsequent cycles does not continue to drop significantly, and remains within the specification range. This is perhaps an indication of some delay in the response of the damper temperature compensation mechanism.

5.3 Endurance/Seal Wear Test

Details of the endurance test performed on Damper C are given in Table 3. The table gives information on each subset of tests performed, including approximate start and end time, the test cycles for which data was recorded, and the laboratory ambient temperature. The approximate start and end temperature values correspond to the damper mid-stroke external surface temperature. Figure 13 presents force-displacement loops for the endurance test. The plots show the first and last cycle force-displacement loops for each test subset.

Even at the slow loading velocity used for the endurance test (0.5 in./sec.), all of the dampers experienced significant temperature rises over the course of the test. At cycle 750, a large fan was positioned to assist in cooling Damper C. This fan was in place for the remainder of the endurance test.

The results of the endurance test indicate some effect of temperature on the damper force output. This effect can be seen in the force-displacement loops for cycles 451-600, 601-750, 751-900, and 901-1050, which were all performed on the same day. At cycle 451, the damper temperature was 58.4 ^{o}F and the force was about 17 kips, and as the test proceeded the temperature increased, to an equilibrium temperature of approximately 124 ^{o}F and a force of about 12 kips. (Note that at cycle 751 a cooling fan was installed, which resulted in a temperature drop of about 15 ^{o}F in the subsequent cycles).

From the start of the endurance test to about cycle 600, the painted surface of the main cylinder that was in contact with the Delrin seal between the outer sleeve and the main cylinder was scraped off. Figure 14 shows of view of the worn area; the upper grey area is the painted surface of the main cylinder, while the lower, shiny area is where the paint was worn off. The worn area extended over about half of the cylinder diameter, and about 6 in. along its length. The extent of paint wear was exacerbated by the lateral loading arrangement. The design of Damper C necessitated that the point of lateral load application be at the top of the outer sleeve, at the location that the Delrin seal guides on the main cylinder. The lateral load was applied by a nylon strap wrapped around the damper. The strap pulled the outer sleeve against the main cylinder and opened up a gap (approximately 1/8 in. wide) between the seal and the main cylinder on the other side. The paint was worn off on the side that the seal was pulled against the main cylinder.

No leakage of viscous fluid was observed at any time during the test. With the exception of the paint wear already described, no other signs of wear were observed.

5.4 Sinusoidal/Energy Dissipation Tests

The results for all of the sinusoidal/energy dissipation tests are presented in Appendix B and summarized numerically in Table 4. The force-displacement plot for each test is shown in the appendix, along with the force, displacement, and energy quantities determined from loops two, three, and four of the five-cycle tests.

Calculation of Energy and Efficiency

The specification required that the damper energy dissipation efficiency be at least 82.5 percent, that is, that the area circumscribed by each force-displacement loop be at least 82.5 percent of the rectangular area defined by the maximum and minimum force and displacement values for that loop. Included in each figure in Appendix B are the quantities required to evaluate the damper efficiency for the second, third, and fourth cycles. The first and last (fifth) cycles were disregarded because the damper force starts and ends at zero for these cycles, resulting in inadequately defined loops for an energy efficiency evaluation. For a given cycle, the damper efficiency is calculated as follows:

$$Efficiency = \frac{Loop\ Area}{(F_{max} - F_{min}) \times (D_{max} - D_{min})} \times 100 \quad \text{(percent)} \qquad \text{Eq. 5.1}$$

where:

$Loop\ Area$ = area of the damper force-displacement loop

F_{max}, F_{min} = maximum and minimum damper force for that cycle

D_{max}, D_{min} = maximum and minimum damper displacement for that cycle

The results of the sinusoidal/energy dissipation tests are summarized in Table 4. The right-hand three columns of the table list the energy dissipated, and in parentheses, the efficiency, for cycles two, three, and four of each test. For all of the tests and cycles, the efficiency is greater than the specified minimum of 82.5 percent. It is noted that for at least one cycle (and typically most of the cycles) of each of the tests, the computed efficiency is actually greater than the theoretical efficiency of a 0.5-power viscous damper (87.5 percent). One possible explanation for this result is that the damper is actually behaving as a lower power damper (i.e., with an exponent less than 0.5), which is supported by the force-velocity behavior identified from the constant-velocity tests (see Figure 8, for example).

5.5 Earthquake Input

The characteristics of the earthquake input test are presented in Figure 6. The input had a duration of 90 seconds, a peak velocity of 20 in./sec., and a peak displacement of 6 in. A plot of damper force against time for the entire earthquake input test is shown in Figure 15a, and the 5 -

35 second portion of the test is shown in Figure 15b. The figures plot both measured damper force and also the calculated damper force based upon the target constitutive law and the measured damper velocity response. From the very good agreement between the measured and calculated damper force, which can be seen in Figure 15b, the Damper C earthquake response is highly predictable.

5.6 Friction Test

The friction tests of Damper C produced a range of results. Four tests yielded reasonable data, and an evaluation of the results of these tests indicated friction force values of 1, 1, 1.8, and 2.8 kips. The 2.8 kip result is slightly above the specification allowable friction force of 2.5 kips, but if the mean value of the four test results is determined (1.65 kips), the estimated damper friction force is well within the specification range.

Several aspects of the friction test contributed to the variability of the results obtained. The nature of the test, i.e., applying a small-force, low rate loading (one kip/min.) using force control via a large range (150 kip) transducer and applied by a servo-actuator system, combined with the intrinsic off-on friction-slip phenomenon, made its execution problematic. Nonetheless, some of the tests produced reasonable results.

The simple friction test, involving disconnecting the damper from the test machine, did not result in any downward movement of the damper.

6. CONCLUSIONS

Damper C performed consistently and well throughout the entire testing/pre-qualification program. The damper showed no signs of degradation or leakage in the endurance test, and the pre- and post-endurance constant-velocity tests did not reveal any change in damper behavior as a result of the endurance test. Paint was scraped off a portion of the surface of the main cylinder of the damper in the endurance test, but this did not affect its function in any way. The 40 °F, 70 °F, and 125 °F constant-velocity tests showed a slight "softening" with increased temperature at velocities up to 5 in./sec., but no discernible temperature effect was seen at higher velocities. The damper performed within the specification range for all of the constant-velocity cyclic tests. Evaluation of the damper force output over all cycles of the cyclic tests showed some reduction in damper force output with increasing cycling. For example, in the case of the 10-cycle sinusoidal test, which represented the energy-equivalent of about two Maximum Credible Earthquakes, the damper force output dropped over the first four cycles but then was stable for the remaining test cycles. But for a few minor instances, the damper force output was within the specification allowable range for all cycles of all tests. The damper energy dissipation efficiency exceeded the specification requirement for all of the sinusoidal tests. The damper energy dissipation characteristics, as evidenced by the force-displacement loops for the sinusoidal tests, were good. The damper performance under the MCE displacement input was very good, and comparison with the theoretical damper force showed that the damper is very predictable even under severe dynamic loading. The frictional resistance of Damper C was found to be about two-thirds of the maximum value allowed by the specification.

TABLES

TABLE 1: TEST PLAN FOR 0.5 POWER DAMPERS

A. Initial Cyclic Tests

Test No.	Group	Vel. (in./sec.)	Ampl. (inches)	Freq. (Hz.)	No. of Cycles	Peak Force (kips)	Energy (kip-in.)	Accum. Energy (kip-in.)	Temp. (°F)	Signal	Comments
I.1	A	1	±1.0	0.25	5	22	447	447	70	Const. Vel.	Force-Vel. Curve
I.2		2	±1.0	0.50	5	32	632	1079	70	Const. Vel.	Force-Vel. Curve
I.3		5	±1.0	1.25	5	50	1000	2079	70	Const. Vel.	Force-Vel. Curve
I.4		10	±1.0	2.50	5	71	1414	3493	70	Const. Vel.	Force-Vel. Curve
I.5		2	±3.0	0.17	5	32	1897	5390	70	Const. Vel.	Force-Vel. Curve
I.6		20	±1.0	5.00	5	100	2000	7390	70	Const. Vel.	Force-Vel. Curve
I.7		5	±3.0	0.42	5	50	3000	10390	70	Const. Vel.	Force-Vel. Curve
I.8		10	±3.0	0.83	5	71	4243	14633	70	Const. Vel.	Force-Vel. Curve
							Group A Total:	14633 k-in.			
I.9	B	15	±3.0	1.25	5	87	5196	5196	70	Const. Vel.	Force-Vel. Curve
I.10		20	±3.0	1.67	5	100	6000	11196	70	Const. Vel.	Force-Vel. Curve
							Group B Total:	11196 k-in.			

B. Endurance/Seal Wear Test[1]

Test No.	Vel. (in./sec.)	Ampl. (inches)	Freq. (Hz.)	No. of Cycles	Peak Force (kips)	Energy (kip-in.)	Prior Energy (kip-in.)	Temp. (°F)	Signal	Comments
W.1	0.5	±6.00	0.0208	1800	15.8	684,254	0	Lab. Ambient	Const. Vel.	Seal Wear Test

1. Manufacturer-specified side load applied to the damper during this test.

C. Cyclic Tests

Test No.	Group	Vel. (in./sec.)	Ampl. (inches)	Freq. (Hz.)	No. of Cycles	Peak Force (kips)	Energy (kip-in.)	Accum. Energy (kip-in.)	Temp. (°F)	Signal	Comments
C.2	A	1	±1.0	0.25	5	22	447	447	70	Const. Vel.	Force-Vel. Curve
C.5	A	5	±1.0	1.25	5	50	1000	1447	70	Const. Vel.	Force-Vel. Curve
C.8	A	20	±1.0	5.00	5	100	2000	3447	70	Const. Vel.	Force-Vel. Curve
C.9	A	5	±3.0	0.42	5	50	3000	6447	70	Const. Vel.	Force-Vel. Curve
C.10	A	10	±3.0	0.83	5	71	4243	10690	70	Const. Vel.	Force-Vel. Curve
							Group A Total:	10690 k-in.			
C.1	B	Force control signal, 2 directions							70	Const. dF/dt	Friction Force
C.4	B	10	±0.6	4.17	5	71	849	849	70	Const. Vel.	Small Amplitude
C.7	B	2	±3.0	0.17	5	32	1897	2746	70	Const. Vel.	Force-Vel. Curve
C.12	B	20	±3.0	1.67	5	100	6000	8746	70	Const. Vel.	Force-Vel. Curve
							Group B Total:	8746 k-in.			
C.13a	C	5	±3.0	0.27	5	50	2622	2622	70	Sinusoidal Displ.	Energy Dissipation
C.13b	C	10	±4.0	0.40	5	71	4964	7586	70	Sinusoidal Displ.	Energy Dissipation
							Group C Total:	7586 k-in.			
C.3	D	2	±1.0	0.50	5	32	632	632	70	Const. Vel.	Force-Vel. Curve
C.6	D	10	±1.0	2.50	5	71	1414	2046	70	Const. Vel.	Force-Vel. Curve
C.11	D	15	±3.0	1.25	5	87	5196	7242	70	Const. Vel.	Force-Vel. Curve
							Group D Total:	7242 k-in.			

Test No.	Group	Vel. (in./sec.)	Ampl. (inches)	Freq. (Hz.)	No. of Cycles	Peak Force (kips)	Energy (kip-in.)	Accum. Energy (kip-in.)	Temp. (°F)	Signal	Comments
C.14	E	20	±6.0	0.53	10	100	20975	20975	70	Sinusoidal Displ.	Energy Dissipation and Endurance
							Group E Total:	20975 k-in.			
C.15	A	Force control signal, 2 directions							125	Const. dF/dt	Friction Force
C.16	A	1	±1.0	0.25	5	22	447	447	125	Const. Vel.	Force-Vel. Curve
C.17	A	2	±1.0	0.50	5	32	632	1079	125	Const. Vel.	Force-Vel. Curve
C.18	A	10	±0.6	4.17	5	71	849	1928	125	Const. Vel.	Small Amplitude
C.19	A	5	±3.0	0.42	5	50	3000	4928	125	Const. Vel.	Force-Vel. Curve
C.20	A	10	±3.0	0.83	5	71	4243	9171	125	Const. Vel.	Force-Vel. Curve
							Group A Total:	9171 k-in.			
C.21	B	15	±3.0	1.25	5	87	5196	5196	125	Const. Vel.	Force-Vel. Curve
C.22	B	20	±3.0	1.67	5	100	6000	11196	125	Const. Vel.	Force-Vel. Curve
							Group B Total:	11196 k-in.			
C.23a	C	5	±2.0	0.40	5	50	1748	1748	125	Sinusoidal Displ.	Energy Dissipation
C.23b	C	10	±6.0	0.27	5	71	7446	9194	125	Sinusoidal Displ.	Energy Dissipation
							Group C Total:	9194 k-in.			
C.24	D	20	±6.0	0.53	10	100	20975	20975	125	Sinusoidal Displ.	Energy Dissipation and Endurance
							Group D Total:	20975 k-in.			

Test No.	Group	Vel. (in./sec.)	Ampl. (inches)	Freq. (Hz.)	No. of Cycles	Peak Force (kips)	Energy (kip-in.)	Accum. Energy (kip-in.)	Temp. (°F)	Signal	Comments
C.25	A	Force control signal, 2 directions							40	Const. dF/dt	Friction Force
C.26		1	±1.0	0.25	5	22	447	447	40	Const. Vel.	Force-Vel. Curve
C.27		2	±1.0	0.50	5	32	632	1079	40	Const. Vel.	Force-Vel. Curve
C.28		10	±0.6	4.17	5	71	849	1928	40	Const. Vel.	Small Amplitude
C.29		5	±3.0	0.42	5	50	3000	4928	40	Const. Vel.	Force-Vel. Curve
C.30		10	±3.0	0.83	5	71	4243	9171	40	Const. Vel.	Force-Vel. Curve
							Group A Total:	9171 k-in.			
C.31	B	15	±3.0	1.25	5	87	5196	5196	40	Const. Vel.	Force-Vel. Curve
C.32		20	±3.0	1.67	5	100	6000	11196	40	Const. Vel.	Force-Vel. Curve
							Group B Total:	11196 k-in.			
C.33a	C	10	±2.0	0.80	5	71	2482	2482	40	Sinusoidal Displ.	Energy Dissipation
C.33b		5	±6.0	0.13	5	50	5244	7726	40	Sinusoidal Displ.	Energy Dissipation
							Group C Total:	7726 k-in.			
C.34	D	20	±6.0	0.53	10	100	20975	20975	40	Sinusoidal Displ.	Energy Dissipation and Endurance
							Group D Total:	20975 k-in.			
Series D Tests performed at lab. ambient temperature (65 - 75 °F) and with lateral load applied to the damper											
D.1		Seismic displacement input for 0.5 Power damper computed by T.Y. Lin International									
D.2		20	±6.0	0.53	10	100	20975	20975		Sinusoidal Displ.	Energy Dissipation and Endurance

Table 2: Damper C Test Datalog

Test	Filename	Test Signal	Time	Mid-Stroke Temp. (^oF)		Comments	
				Start	End		
70 ^oF soak started 7:30 pm, 5/3/95							
I.1	950504.01	sawi1	11:41 am	72	74	sawc1	TCtopbox not functioning in today's tests
I.2	950504.02	sawi2	11:46 am	73	74	sawc12	
I.3	950504.03	sawi3	11:51 am	72	73	sawc2	
I.4	950504.04	sawi4	11:56 am	72	75	sawc13	all 4 pumps to 3/8 displ. system oil at 120F
I.5	950504.05	sawi5	12:01 pm	74	76	sawc8	
I.6	950504.06	sawi6	12:06 pm	75	76	sawc3	
I.7	950504.07	sawi7	12:11 pm	76	78	sawc4	
I.8	950504.08	sawi8	12:16 pm	78	79	sawc5	system oil at 155F after this test
I.9	950504.09	sawi9	4:21 pm	72	74	sawc14	
I.10	950504.10	sawi10	4:26 pm	74	76	sawc9	

Test	Filename	Test Signal	Time	Mid-Stroke Temp. (^oF) Start	Mid-Stroke Temp. (^oF) End	Comments
Remove temp. box, set up lateral load						
Endurance Test: 5/5 - 5/9/95 (950505.01 - 950509.05, 12 test datafiles)						
Remove lateral load, reinstall temp. box						
70 ^oF soak started: 7:35 pm, 5/9/95						
C.2	950511.01	sawc1	9:22 am	68	68	
C.5	950511.02	sawc2	9:27 am	69	70	
C.8	950511.03	sawc3	9:35 am	68	69	all 4 pumps to 3/8 displ. for next tests
C.9	950511.04	sawc4	9:40 am	68	70	
C.10	950511.05	sawc5	9:45 am	71	72	
Force-cooled the damper at 50 ^oF for 40 min., then reset the box temp. to 70 ^oF Repaired TCtopbox						
C.4	950511.06	sawc7	11:24 am	75	76	
C.7	950511.07	sawc8	11:29 am	76	77	
C.12	950511.08	sawc9	11:34 am	78	79	
Force-cooled the damper at 40 ^oF for 40 min., then reset the box temp. to 70 ^oF						
C.1	950511.09	frict	1:26 pm	78	78	
C.1	950511.10	frictneg	1:30 pm	78	78	
C.13a	950511.11	sinc10	1:38 pm	78	77	
C.13b	950511.12	sinc11	1:43 pm	77	78	

Test	Filename	Test Signal	Time	Mid-Stroke Temp. (°F)		Comments
				Start	End	
Force-cooled the damper at 40 °F for 40 min., then reset the box temp. to 70 °F Repaired TCtopstr						
C.3	950511.13	sawc12	3:14 pm	76	76	
C.6	950511.14	sawc13	3:19 pm	76	76	scalar = 1.1
C.11	950511.15	sawc14	3:24 pm	80	77	scalar = 1.25
Force-cooled the damper at 40 °F for 40 min., then reset the box temp. to 70 °F						
C.14	950511.16	sinc15	4:43 pm	80	83	scalar = 1.0
125 °F soak started: 5:00 pm, 5/11/95						
C.15	950512.01	frict	9: 23 am	101	101	hit 4.99K limit without slip
C.15	950512.02	frict	9:28 am	101	101	retest with 8K limit but ran out of disk space
C.15	950512.03	frict	10:21 am	99	99	retest; o.k.
C.15	950512.04	frictneg	10:27 am	98	98	
C.16	950512.05	sawc1	10:34 am	96	96	
C.17	950512.06	sawc12	10:41 am	96	99	
C.18	950512.07	sawc7	10:46 am	100	98	4 pumps
C.19	950512.08	sawc4	10:51 am	97	98	"
C.20	950512.09	sawc5	10:56 am	101	104	"
Observed odd behavior of the stroke thermocouples; conditioning box not providing adequate coverage of the damper. Fabricated and installed an 11.75" extension on the top of the existing box and re-ran all tests, 950512.01 - 950512.09.						
C.15	950512.10	frict	12:50 pm	120	120	

Test	Filename	Test Signal	Time	Mid-Stroke Temp. (°F) Start	Mid-Stroke Temp. (°F) End	Comments
C.15	950512.11	frictneg	12:55 pm	120	120	
C.16	950512.12	sawc1	12:59 pm	120	120	
C.17	950512.13	sawc12	1:04 pm	120	120	
C.18	950512.14	sawc7	1:09 pm	120	120	
C.19	950512.15	sawc4	1:14 pm	120	120	
C.20	950512.16	sawc5	1:19 pm	121	122	
Force-cooled the damper at 85 °F for 35 min., then reset the box temp. to 125 °F						
C.21	950512.17	sawc14	2:20 pm	126	129	scalar = 1.25
C.22	950512.18	sawc9	2:25 pm	131	132	scalar = 1.15
C.23a	950512.19	sinc18	3:41 pm	126	128	
C.23b	950512.20	sinc19	3:46 pm	128	132	
C.24	950512.21	sinc15	4:51 pm	131	-	
40 °F soak started: 9:10 pm, 5/14/95						
C.25	950515.01	frict	9:10 am	41	42	removed wire pot on damper - not functioning at 40 °F (lubricant soldifying?)
C.25	950515.02	frictneg	9:14 am	42	42	
C.26	950515.03	sawc1	9:22 am	42	43	
C.27	950515.04	sawc12	9:28 am	43	44	
C.28	950515.05	sawc7	9:33 am	43	45	4 pumps
C.29	950515.06	sawc4	9:38 am	45	45	"

Test	Filename	Test Signal	Time	Mid-Stroke Temp. (^{o}F)		Comments
				Start	End	
C.30	950515.07	sawc5	9:43 am	46	48	"
Force-cooled the damper at 15 ^{o}F for 35 min., then reset the box temp. to 40 ^{o}F for 80 min.						
C.31	950515.08	sawc14	11:37 am	49	50	scalar = 1.25
C.32	950515.09	sawc9	11:42 am	51	53	scalar = 1.15
Force-cooled the damper at 0 ^{o}F for 40 min., then reset the box temp. to 40 ^{o}F for 70 min.						
C.33a	950515.10	sinc16	11:31 am	50	51	
C.33b	950515.11	sinc17	1:36 pm	52	53	
Force-cooled the damper at 0 ^{o}F for 40 min., then reset the box temp. to 40 ^{o}F for 60 min.						
C.34	950515.12	sinc15	3:15 pm	50	60	
Remove temp. box, set up lateral load						
D.1	950516.01	eqd0.5	8:30 am	62	65	lateral load applied
D.2	950516.02	sinc15	9:14 am	70	78	lateral load applied
END OF TEST PROGRAM						

Table 3: Damper C - Endurance Test Datalog

Data File	No. of Cycles	Absolute No. of Cycles	Cycles Recorded	Approx. Time		Approx. Temp. (°F)		Lab. Ambient (°F)
				Start	End	Start	End	
950505.01	150	1 - 150	1-10,20,...140,145-150	11:45 am	1: 45 pm	62	110	62
950505.02	150	151 - 300	1-5,10,20,...140,145-150	1:59 pm	3:59 pm	111	154	60
950505.03	150	301 - 450	1-5,10,20,...,140,145-150	4:30 pm	6:30 pm	156	156	67
950508.01	150	451 - 600	1-10,20,...140,145-150	8:21 am	10:21 am	59	113	59
950508.02	150	600 -750	1-5,10,20,...140,145-150	10:25 am	12:25 pm	112	143	61
950508.03	150	751 - 900	1-5,10,20,...140,145-150	1:53 pm	3:53 pm	113	123	64
950508.04	150	901-1050	1-5,10,20,...140,145-150	3:59 pm	5:59 pm	121	-	58
950509.01	150	1051 - 1200	1-10,20,...140,145-150	8:21 am	10:21 am	67	98	49
950509.02	150	1201 - 1350	1-5,10,20,...140,145-150	10:26 am	12:26 pm	98	115	55
950509.03	150	1351 - 1500	1-5,10,20,...140,145-150	12:30 pm	2:30 pm	115	117	58
950509.04	150	1501 - 1650	1-5,10,20,...140,145-150	2:57 pm	4:57 pm	111	122+	59
950509.05	150	1651 - 1800	1-5,10,20,...140,145-150	5:00 pm	7:00 pm	121	120	57

Table 4: Damper C - Energy Dissipation in Sinusoidal Tests

Test No.	Datafile (Signal)	Amplitude [+/- inches]	Frequency [Hz]	No. of Cycles	Nominal Temp. [^oF]	Energy Dissipated [kip-in] (Efficiency [%])		
						Cycle 2	Cycle 3	Cycle 4
C.13a	950511.11 (sinc10)	3.0	0.27	5	70	564.3 (85.5)	535.8 (86.9)	518.4 (87.3)
C.13b	950511.12 (sinc11)	4.0	0.40	5	70	missing datafile		
C.14	950511.16 (sinc15)	6.0	0.53	10	70	2011.2 (91.5)	1915.8 (92)	1874.5 (91.7)
C.23a	950512.19 (sinc18)	2.0	0.80	5	40	335.7 (85.7)	322.4 (87.2)	312.8 (87.4)
C.23b	950512.20 (sinc19)	6.0	0.13	5	40	1453.1 (86.8)	1383.3 (88.1)	1348.9 (88.5)
C.24	950512.21 (sinc15)	6.0	0.53	10	40	1916.8 (90.7)	1831.5 (91.4)	1792.7 (91.3)
C.33a	950515.10 (sinc16)	2.0	0.40	5	125	513.7 (85.7)	487.2 (87.7)	477.6 (88.5)
C.33b	950515.11 (sinc17)	6.0	0.27	5	125	1243.3 (87.9)	1199.3 (88.2)	1174.1 (87.8)
C.34	950515.12 (sinc15)	6.0	0.53	10	125	2027.2 (91.4)	1929.4 (92.3)	1890 (92.1)
D.2	950516.02 (sinc15)	6.0	0.53	10	ambient	1996 (92)	1919 (91.9)	1881.3 (92.1)

FIGURES

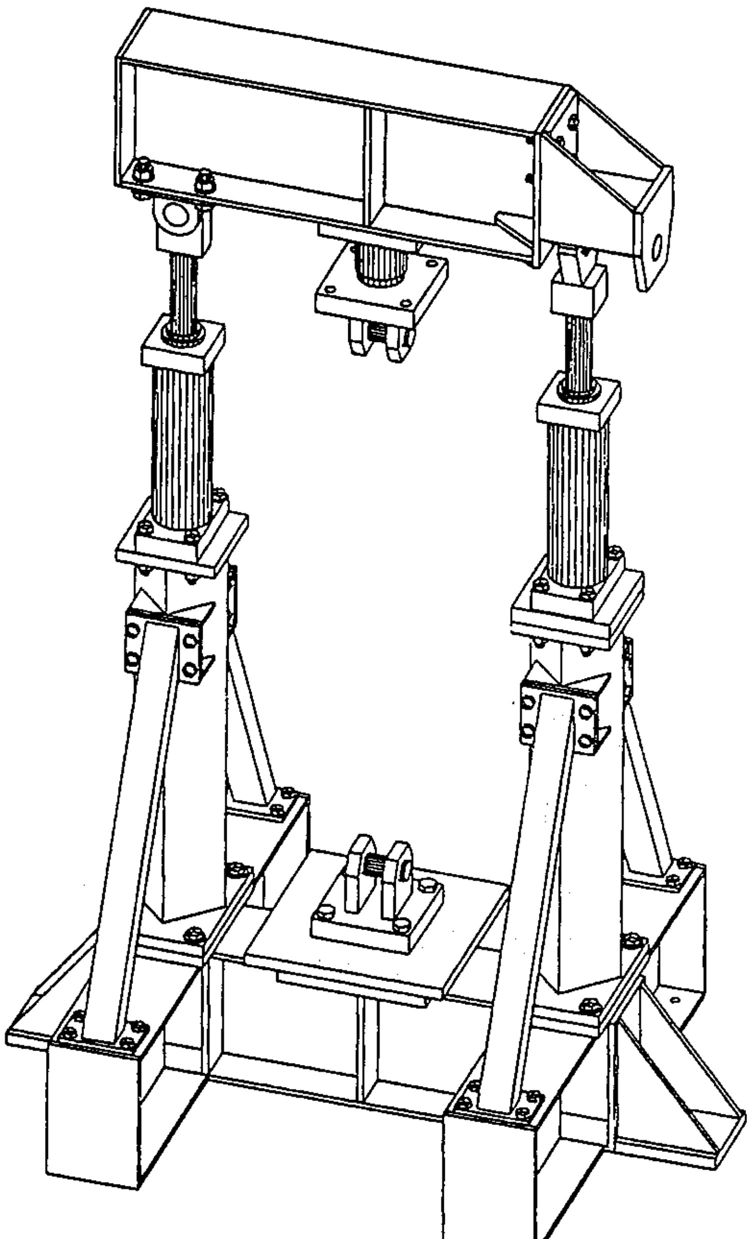


Figure 1. Damper Test Machine

Figure 2. Temperature Box Around Damper in Test Machine

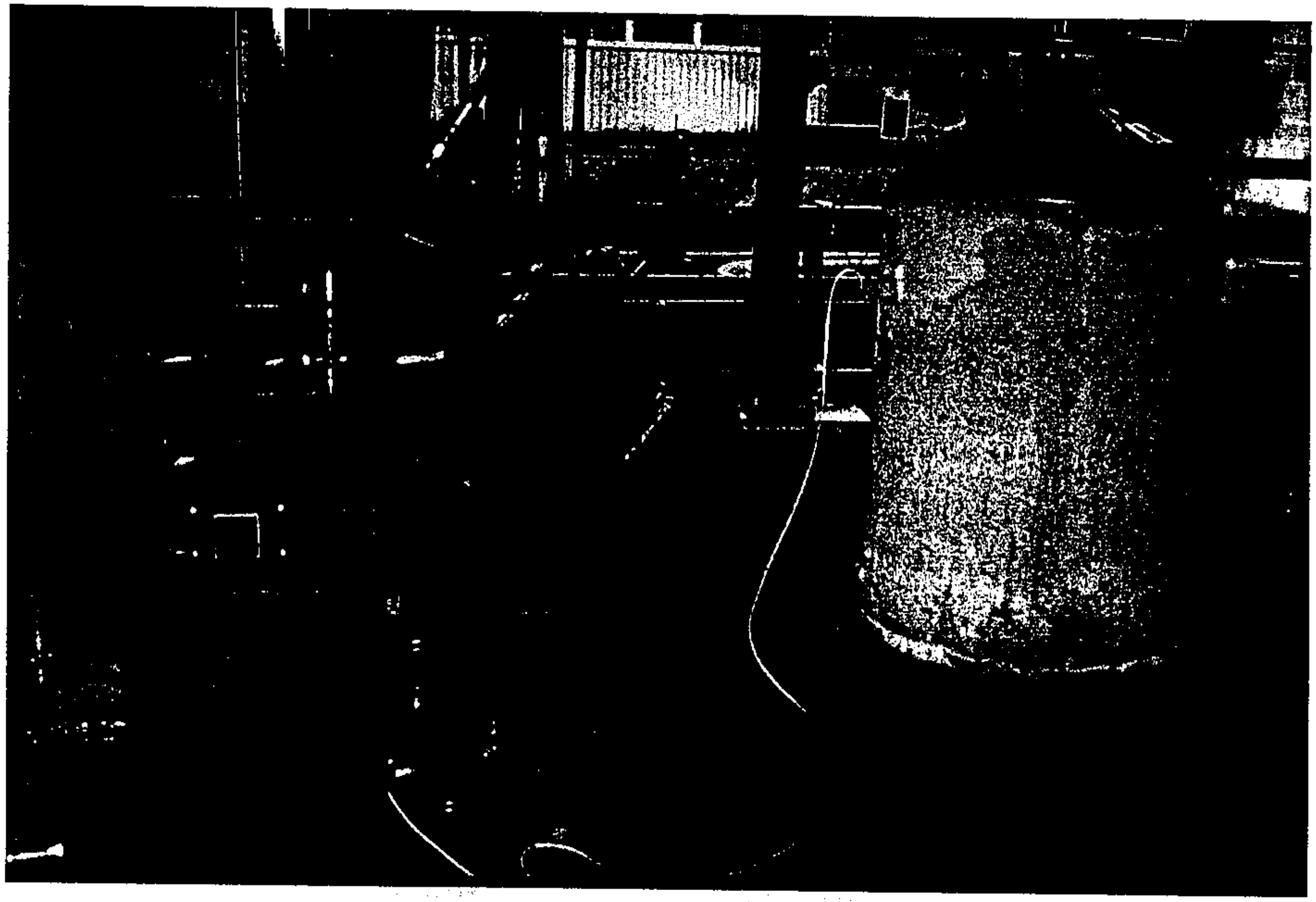
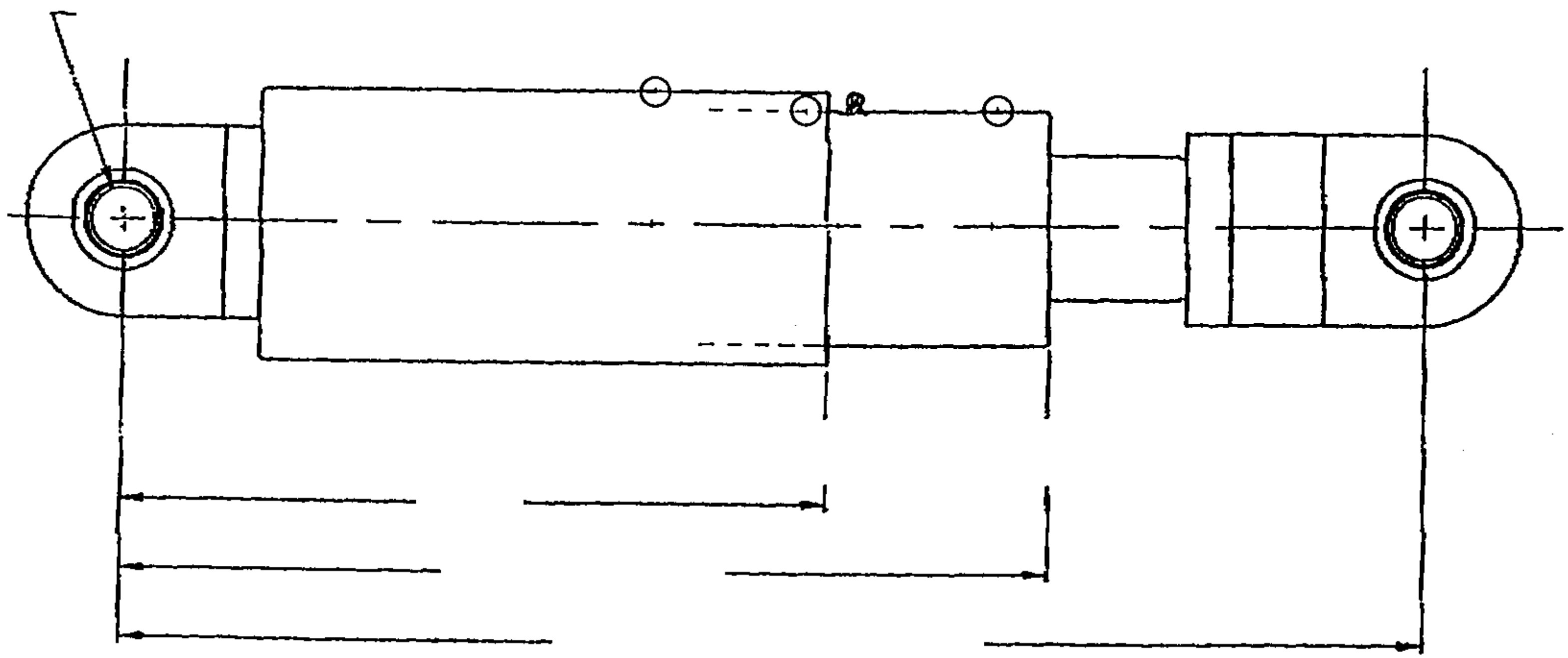


Figure 3. Liquid Nitrogen Cooling System



○ - Approximate locations of thermocouples for testing program

Figure 4. Side View of Damper C

Figure 5. Damper C in Test Machine with Side Load Applied

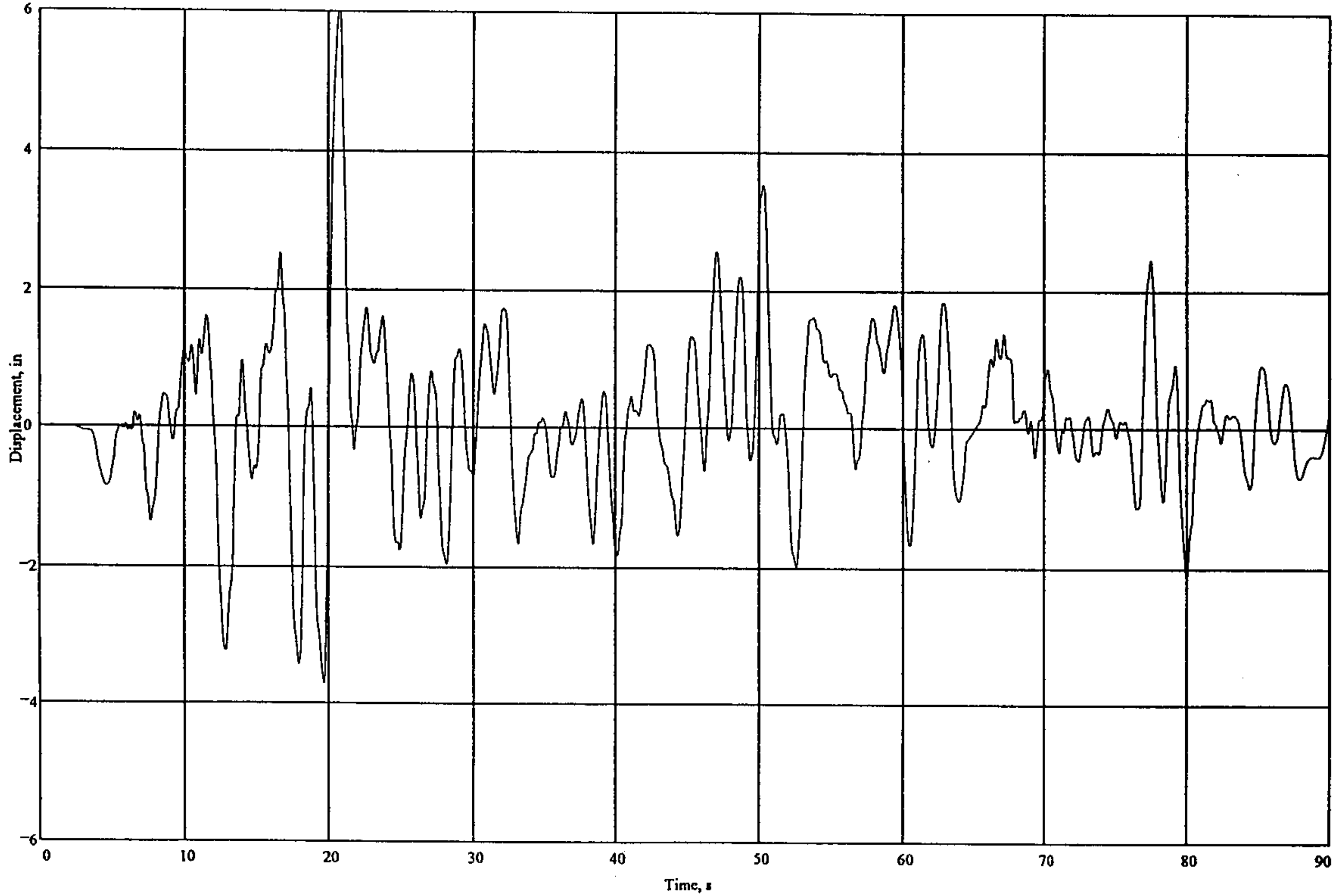


Figure 6. Analytically-Determined MCE Earthquake Loading for 0.5-Power Damper

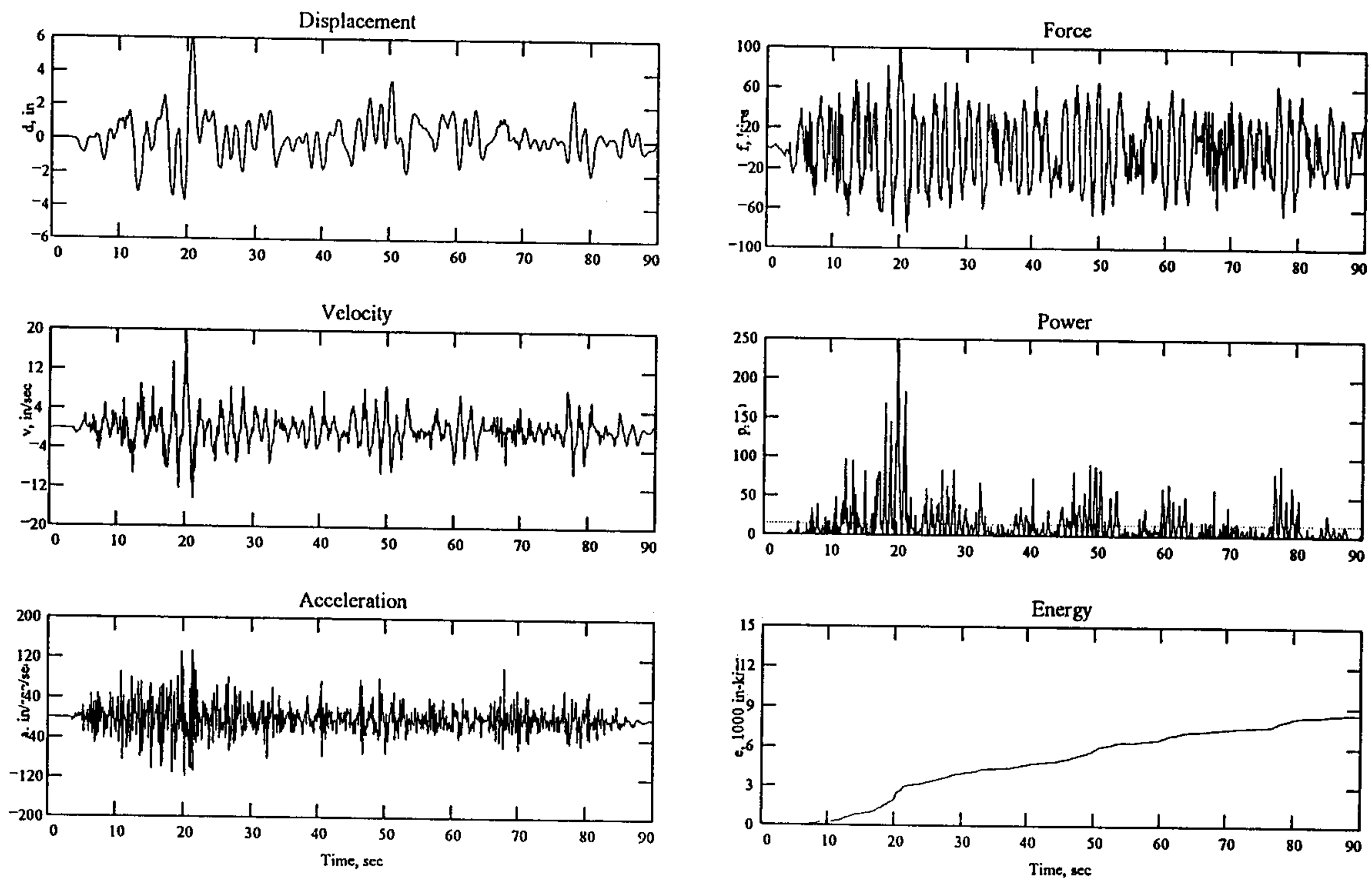


Figure 6. Analytically-Determined MCE Earthquake Loading for 0.5-Power Damper

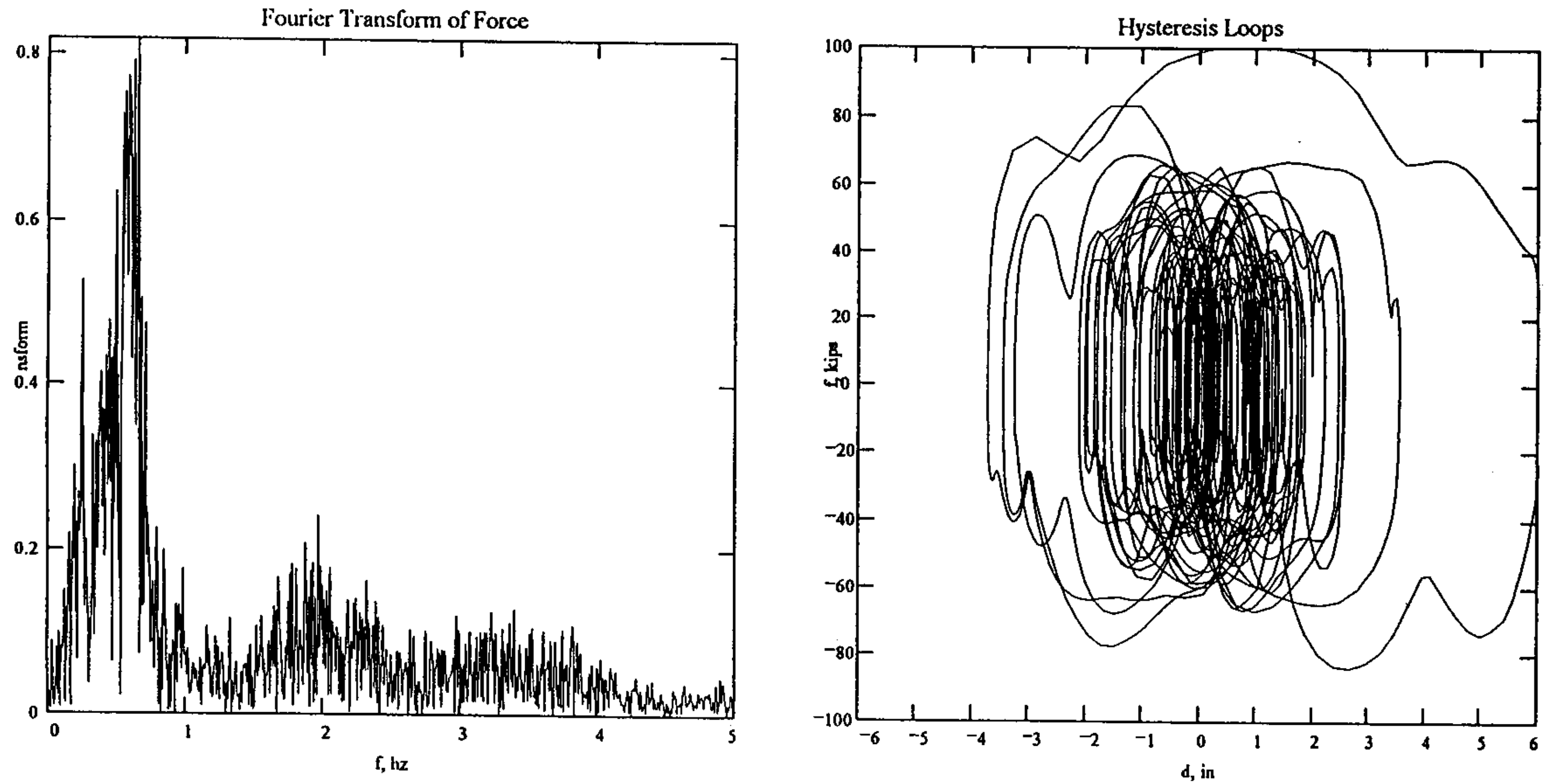


Figure 6. Analytically-Determined MCE Earthquake Loading for 0.5-Power Damper

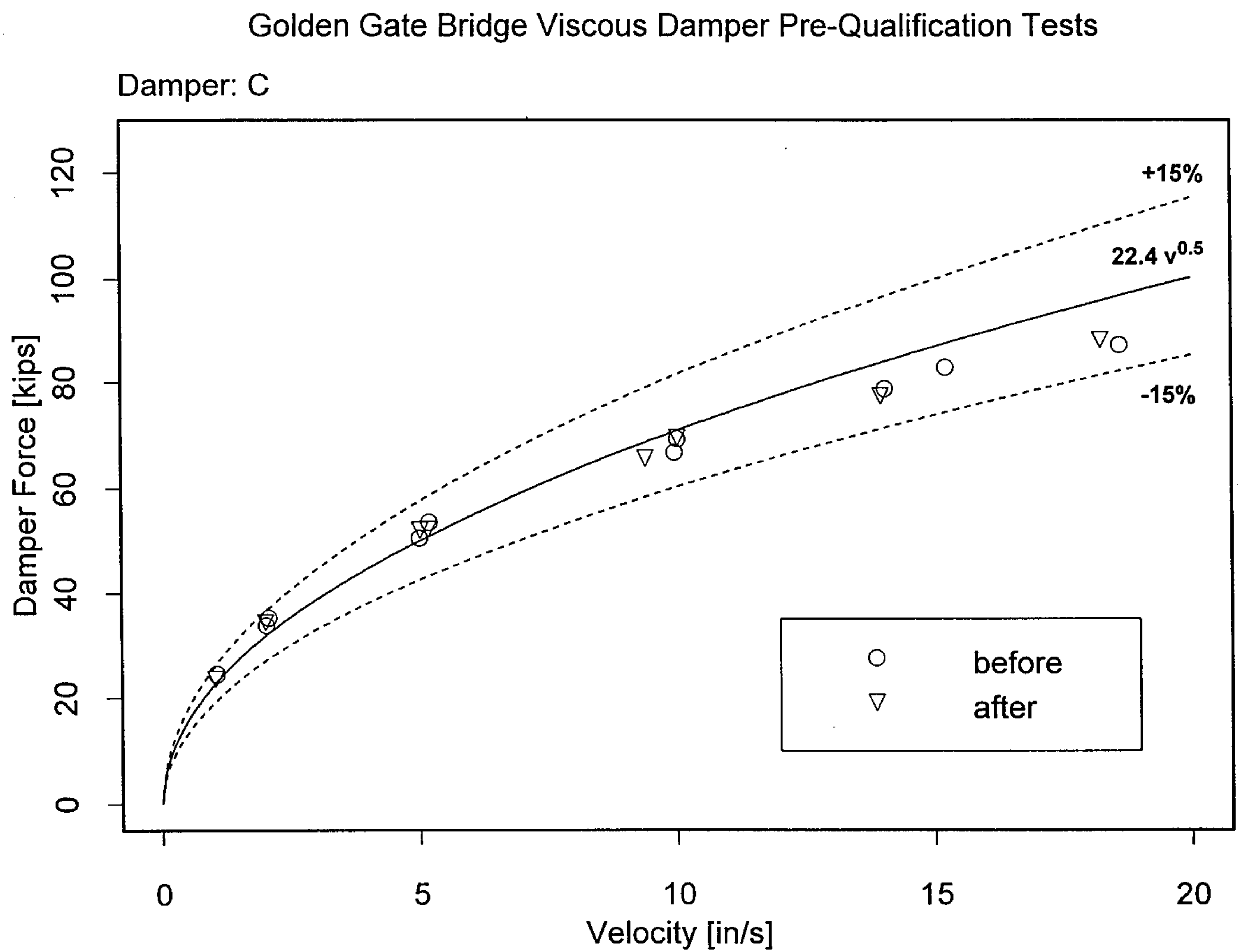


Figure 7. **Damper Force versus Velocity from 70 °F Cyclic Constant-Velocity Tests Before and After the Endurance Test**

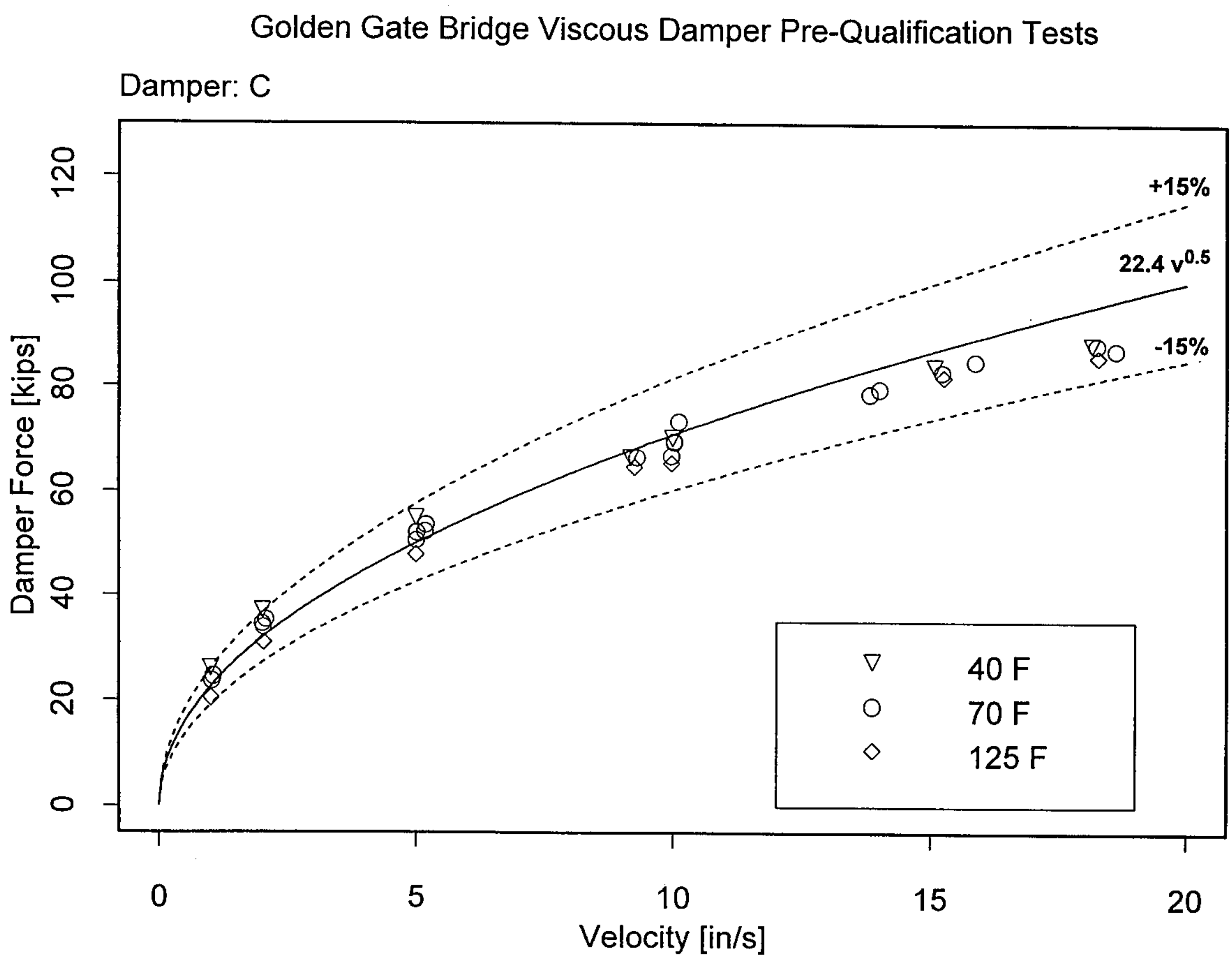


Figure 8. Damper Force versus Velocity for all Cyclic Constant-Velocity Tests

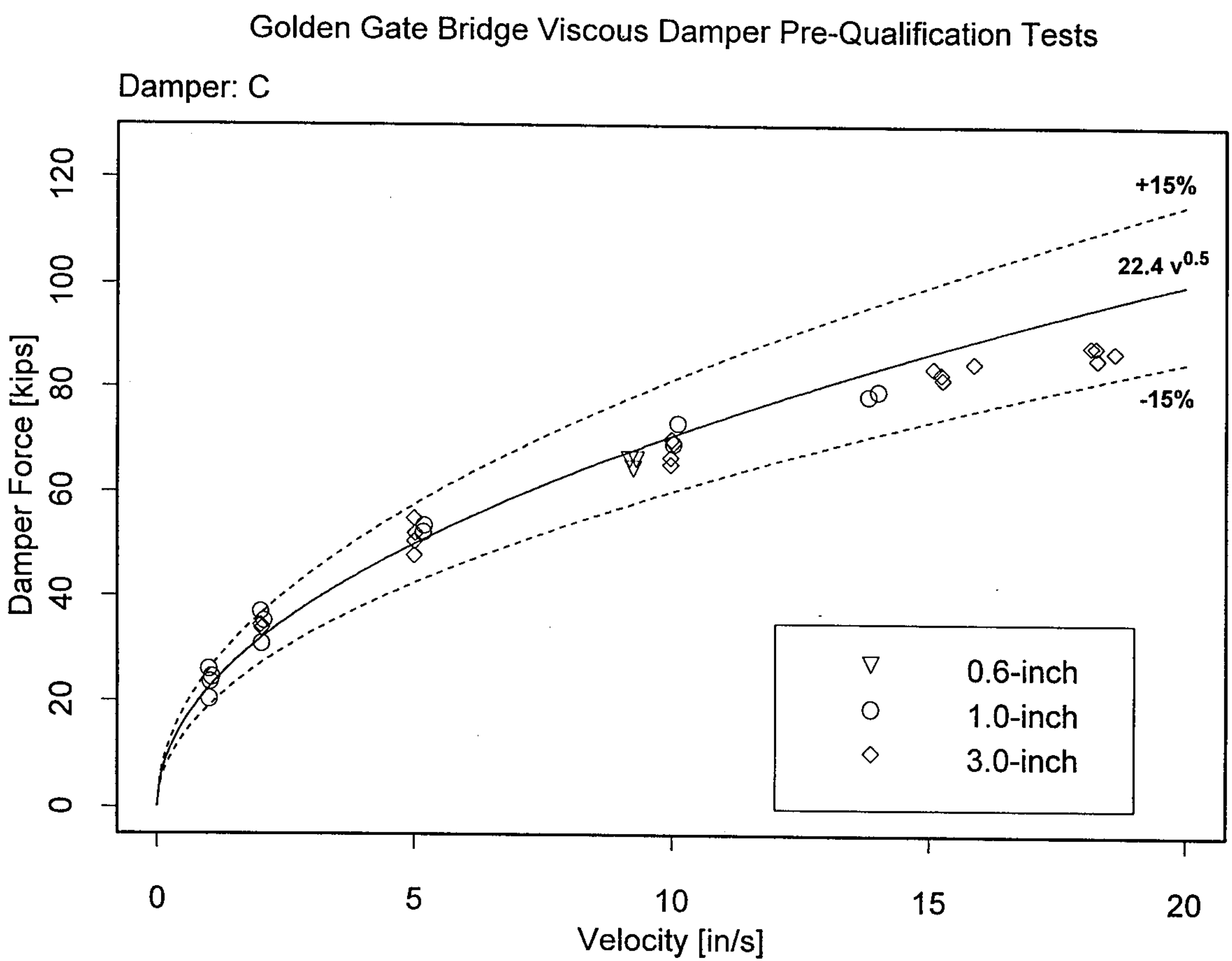


Figure 9. **Damper Force versus Velocity in terms of Amplitude for all Cyclic Constant-Velocity Tests**

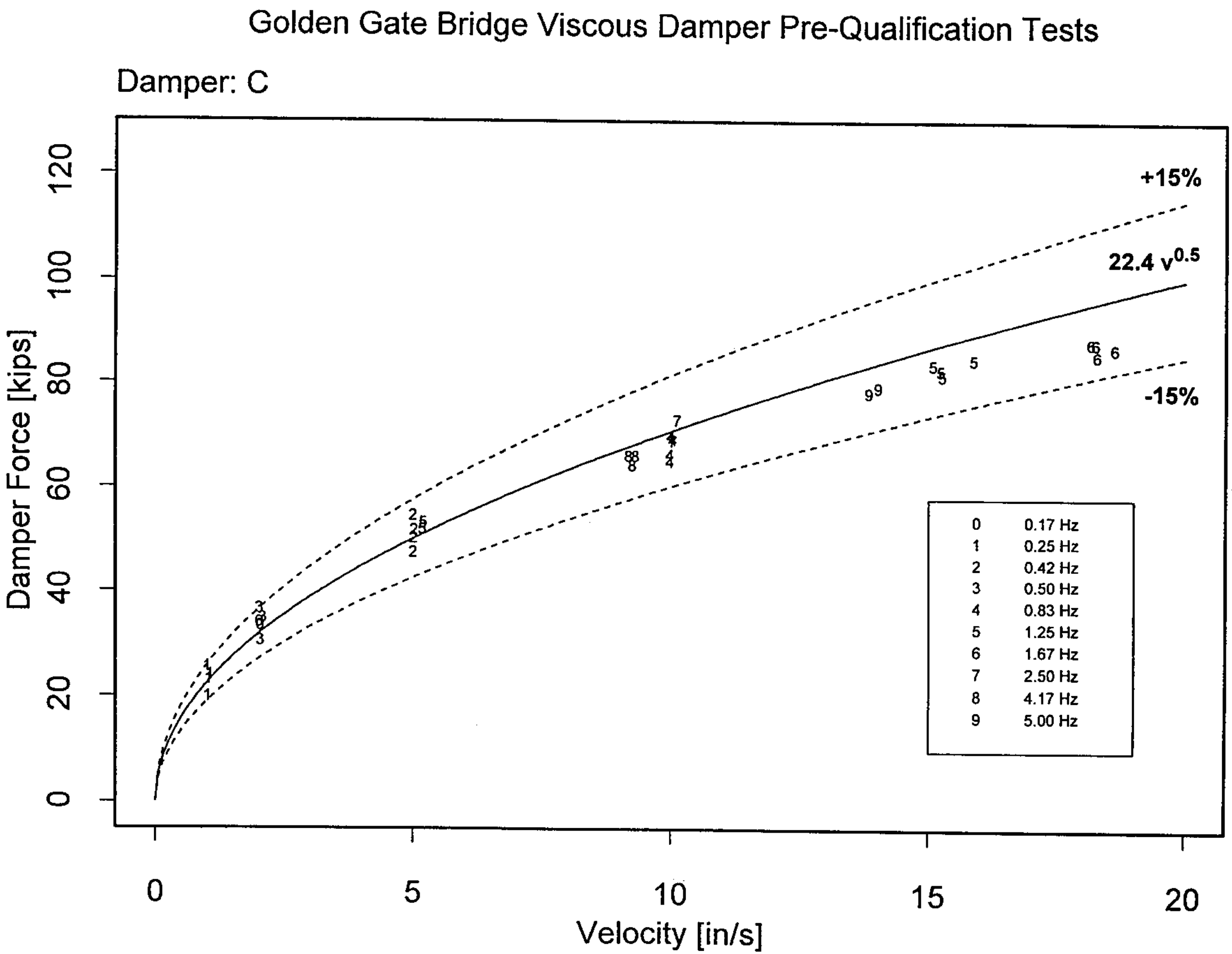


Figure 10. Damper Force versus Velocity in terms of Frequency for all Cyclic Constant-Velocity Tests

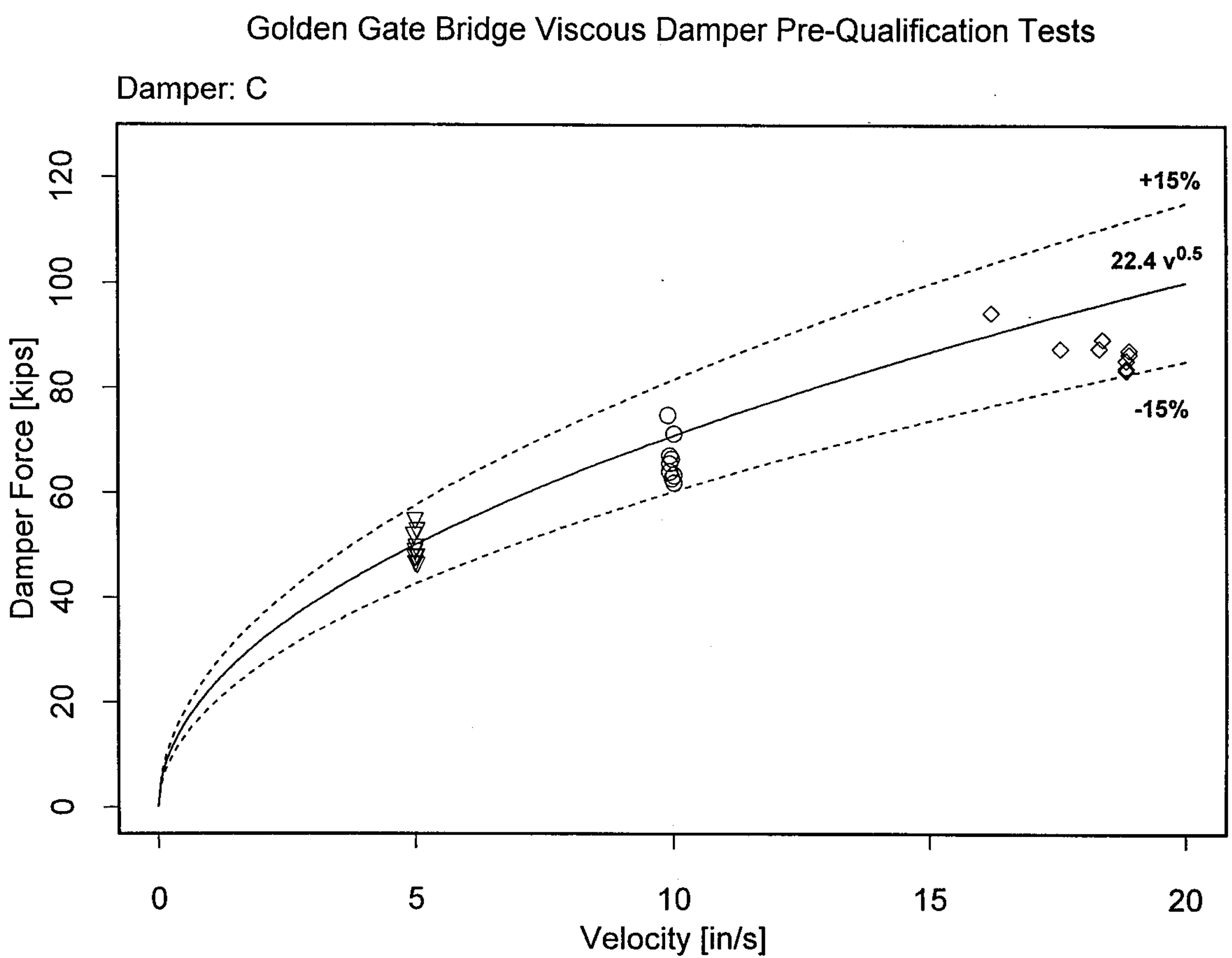


Figure 11. Damper Force versus Velocity for Each Half-Cycle of Constant-Velocity Tests I.7, I.8 and I.10

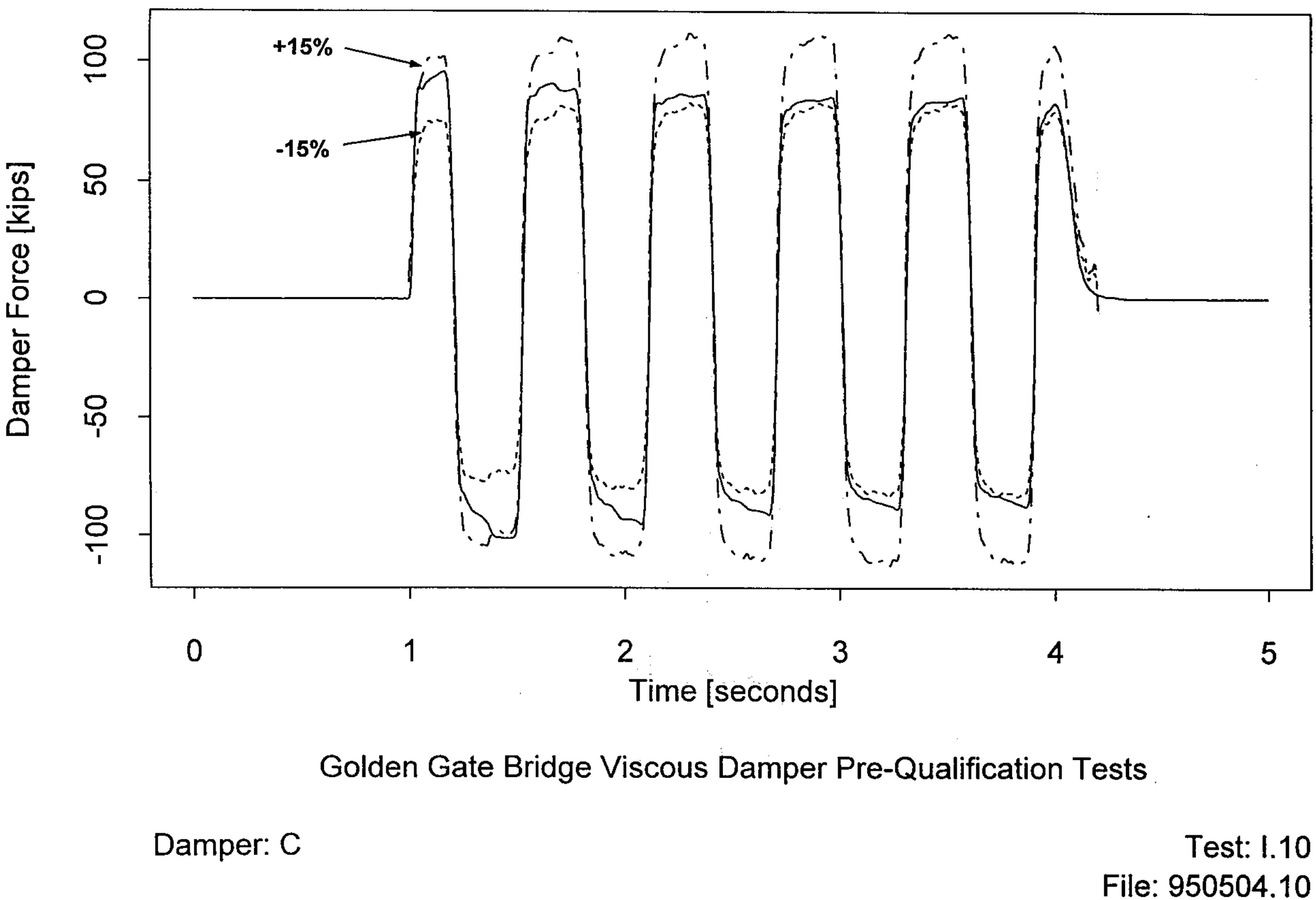


Figure 12a. Measured and Calculated Force Time-Histories for Test I.10 (+/- 3 inches, 15 inches/sec.)

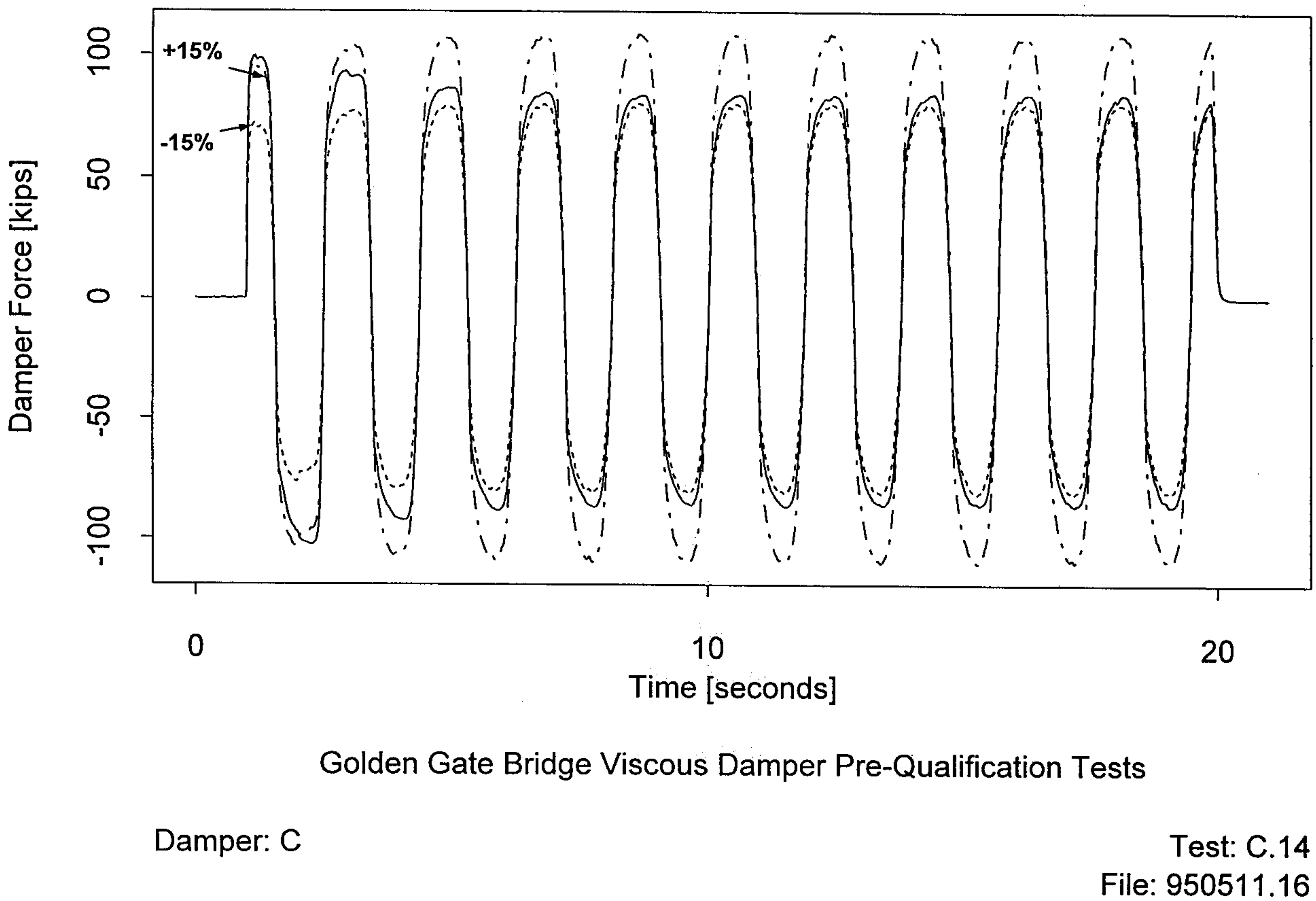


Figure 12b. Measured and Calculated Force Time-Histories for Test C.14 (+/- 6 inches, 20 inches/sec.)

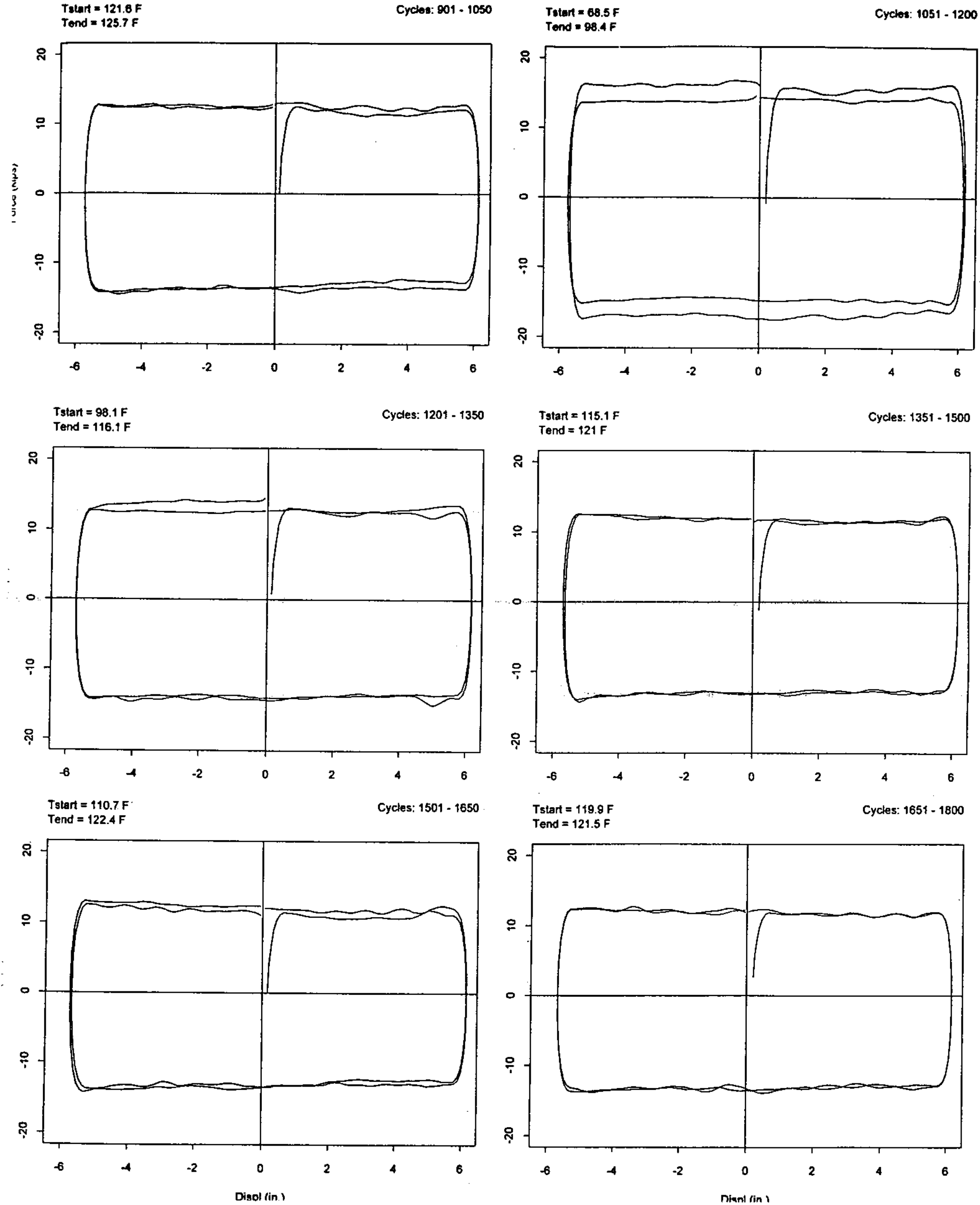


Figure 13 cont. Force-Displacement Loops for Damper C Endurance Test

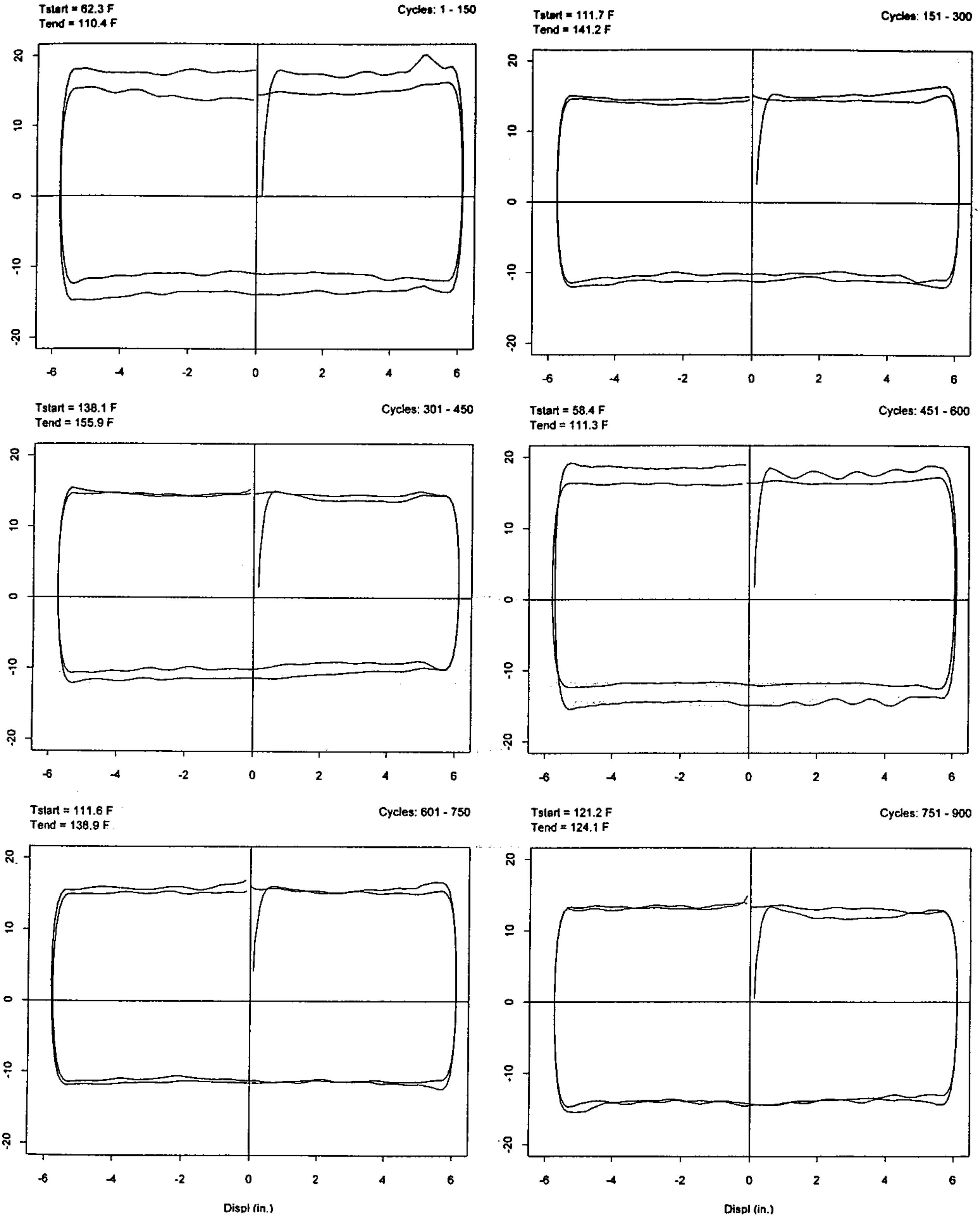


Figure 13. Force-Displacement Loops for Damper C Endurance Test

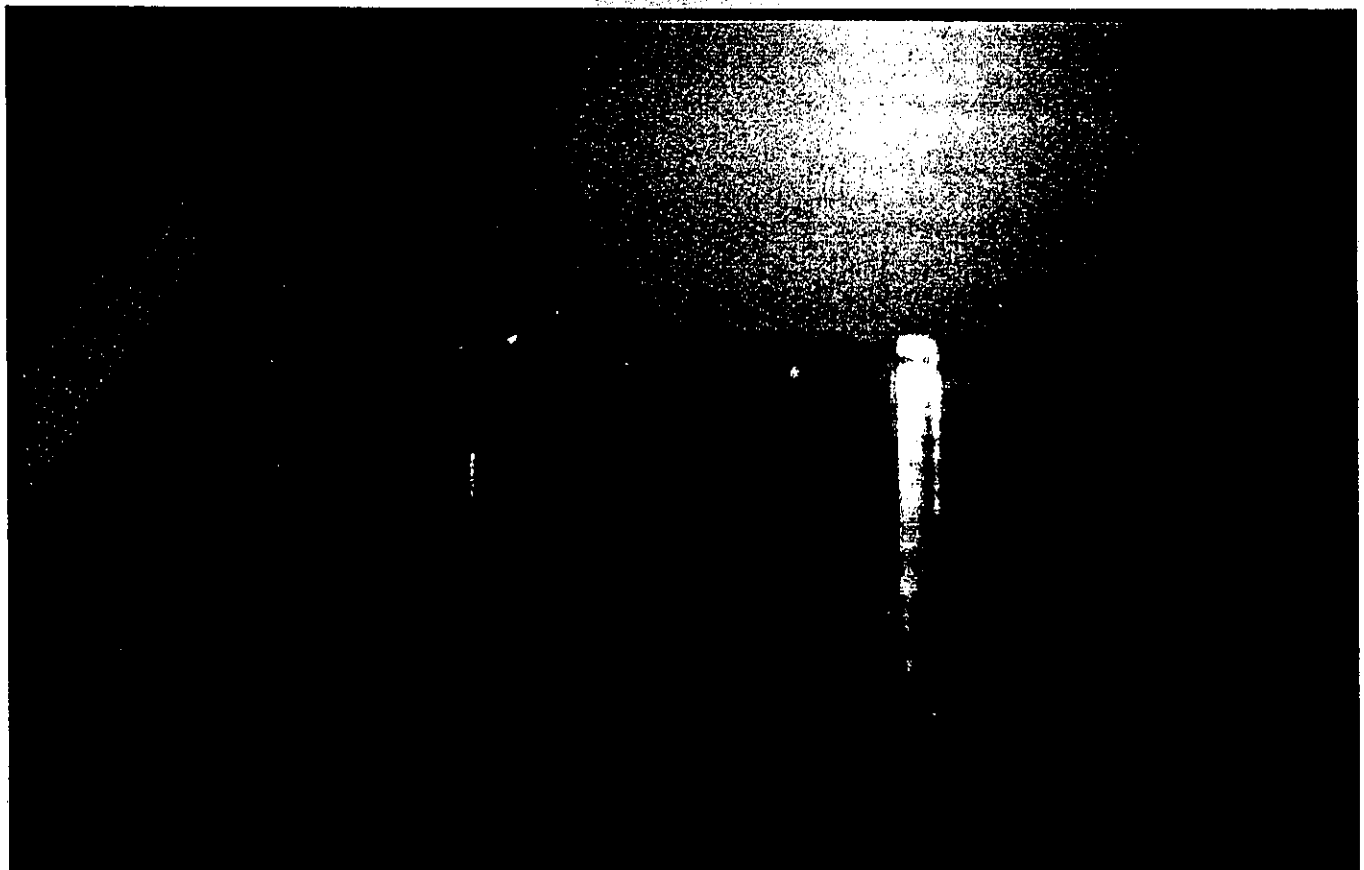
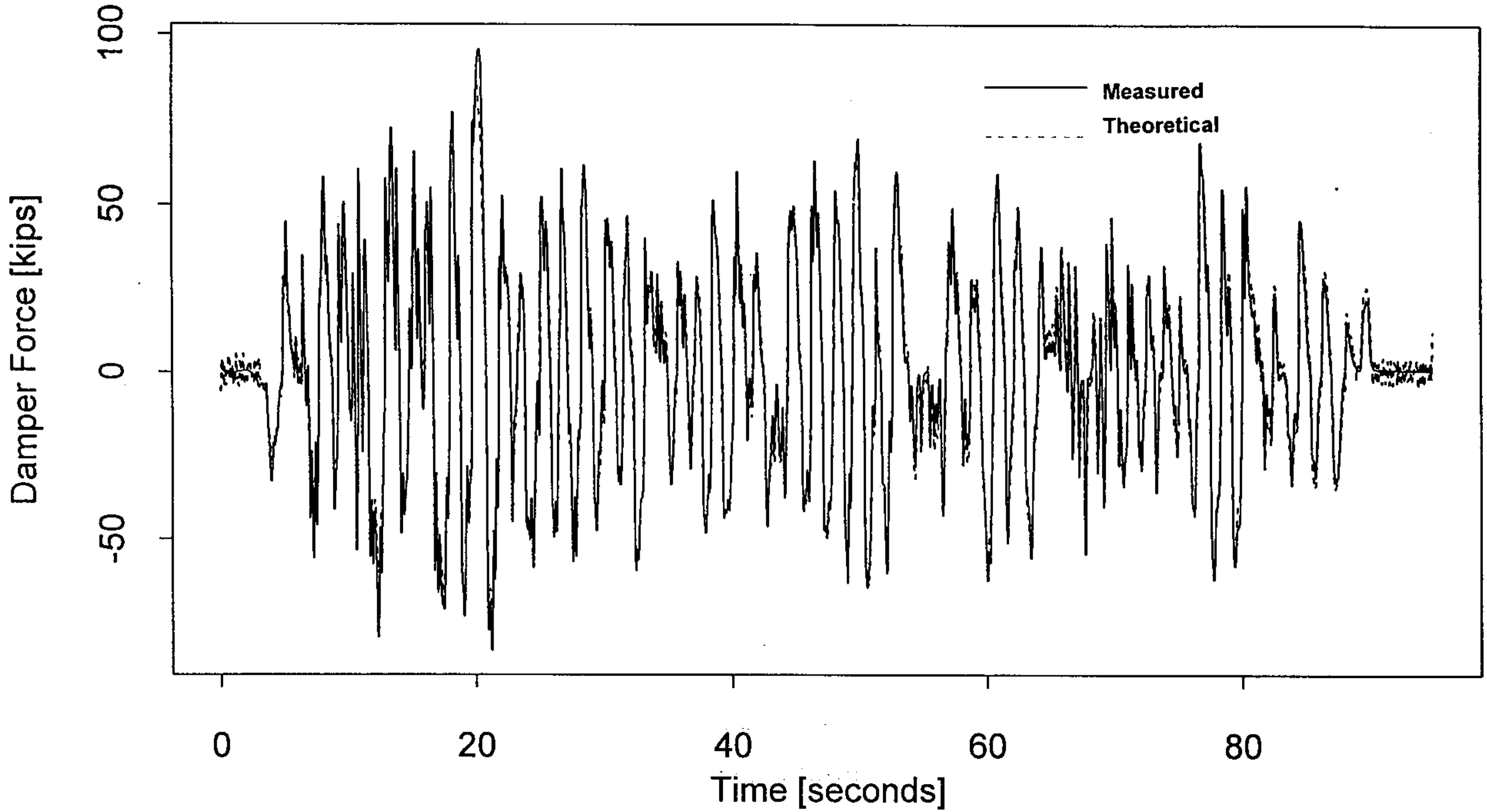


Figure 14. Paint Wear on Main Body of Damper C from Endurance Test

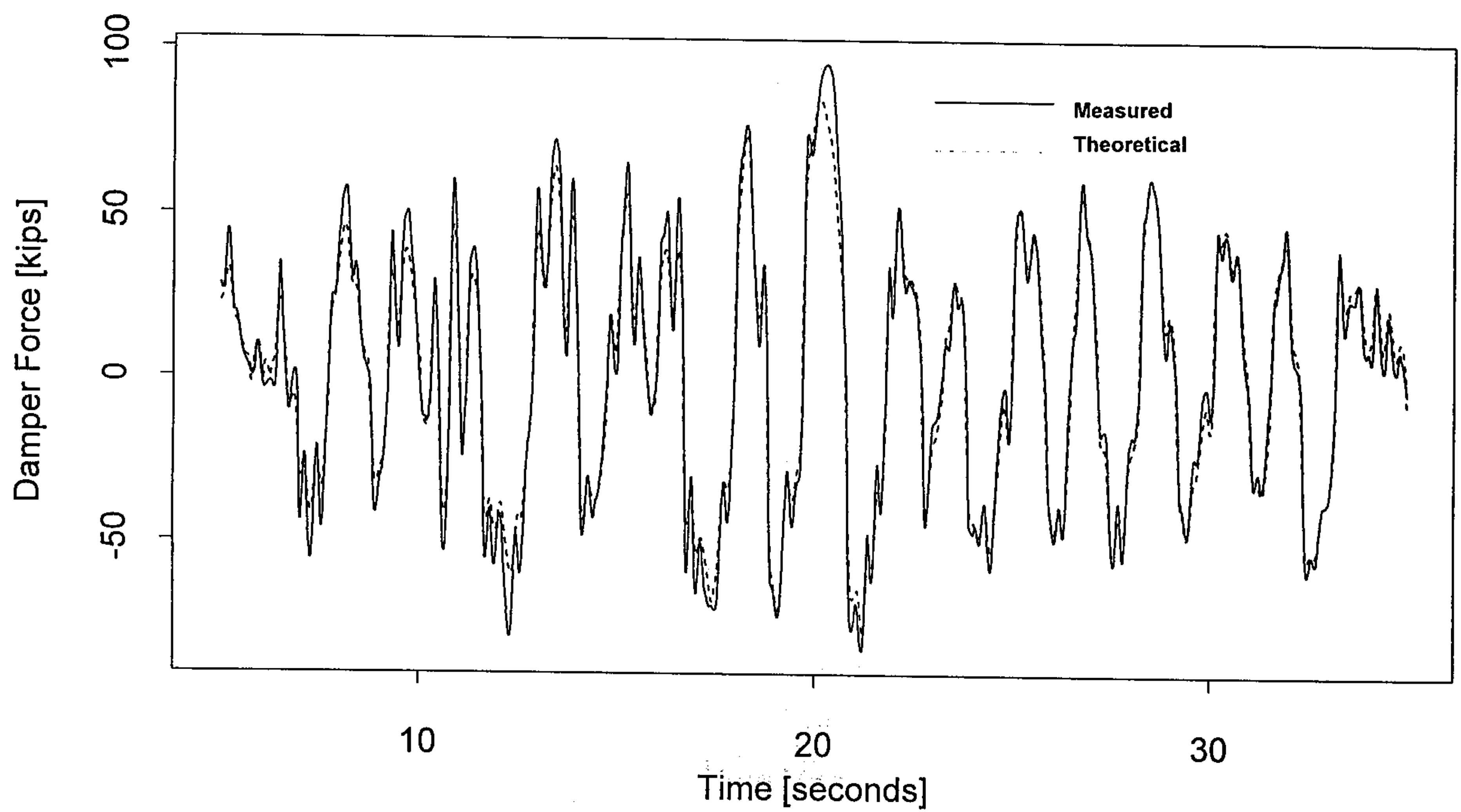


Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Damper: C

Test: D.1
File: 950516.01

Figure 15a. Theoretical and Measured Damper Force for MCE Earthquake Test



Golden Gate Bridge Viscous Damper Pre-Qualification Tests

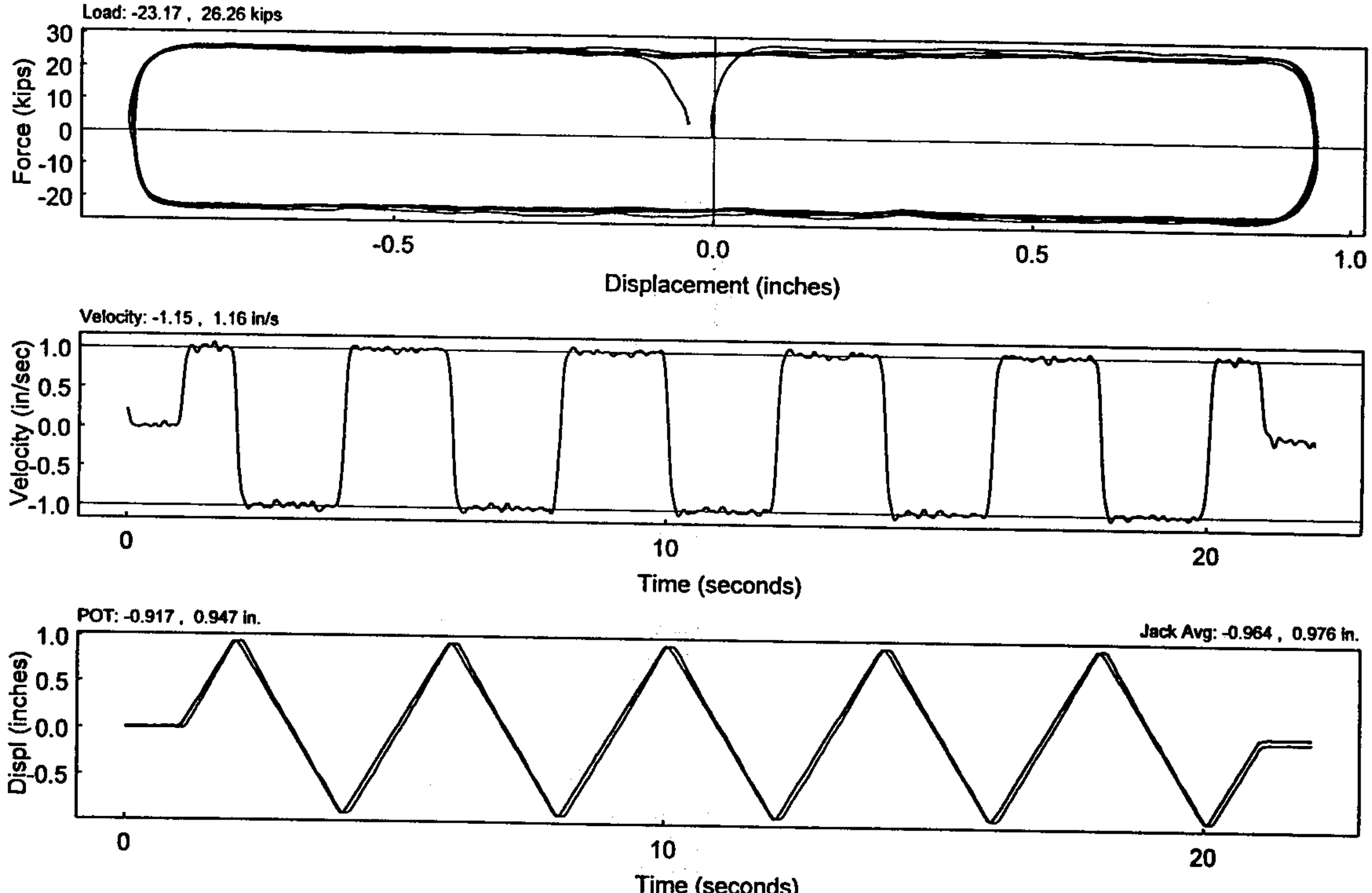
Damper: C

Test: D.1
File: 950516.01

Figure 15b. Theoretical and Measured Damper Force for MCE Earthquake Test, 5 - 35 seconds

Appendix A

Results for All Cyclic Tests



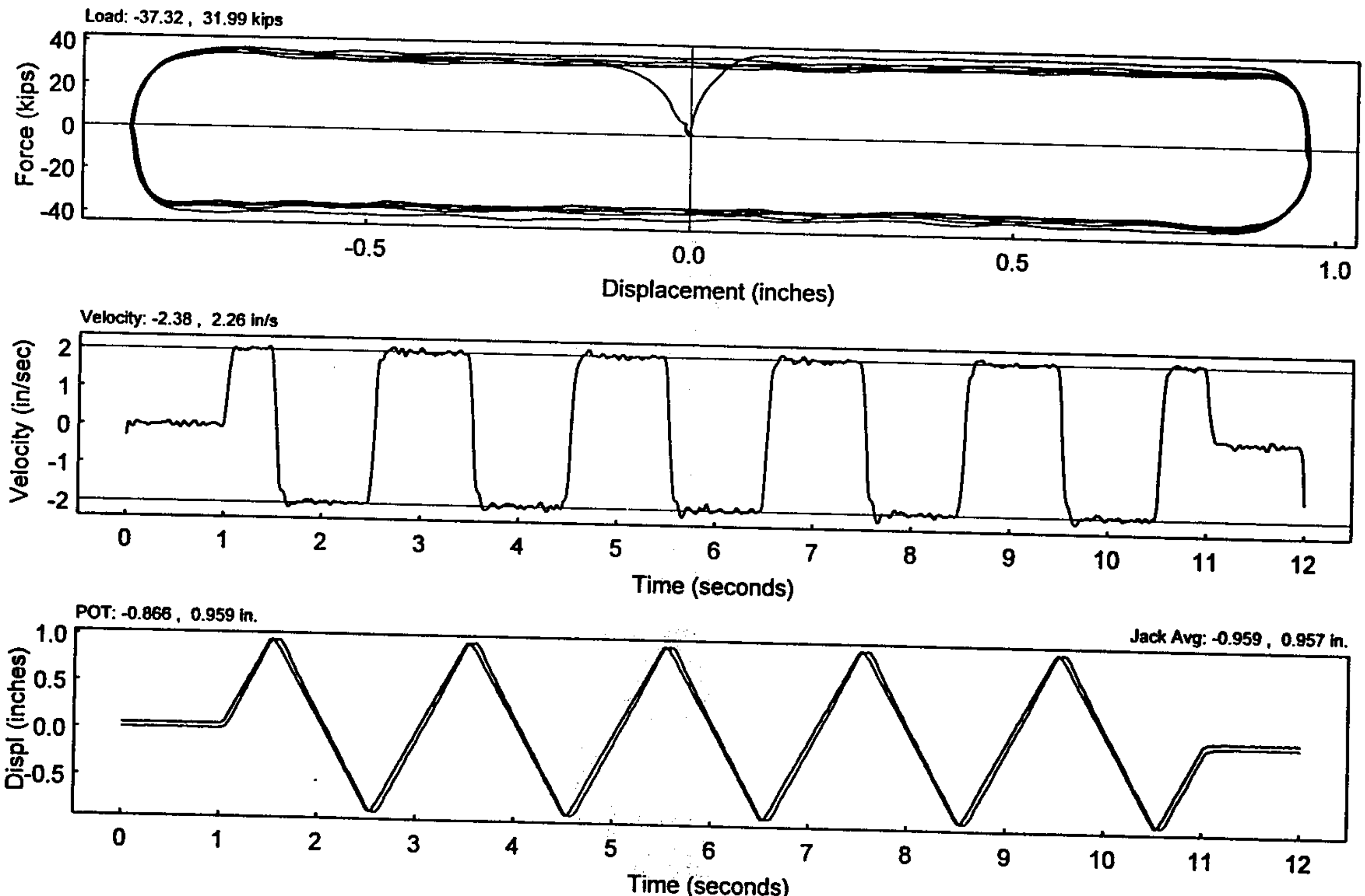
Damper: C

Test: sawi1
Target Velocity: 1 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 4 13:34:24 1995
Function: cvplot.s

File: 950504.01



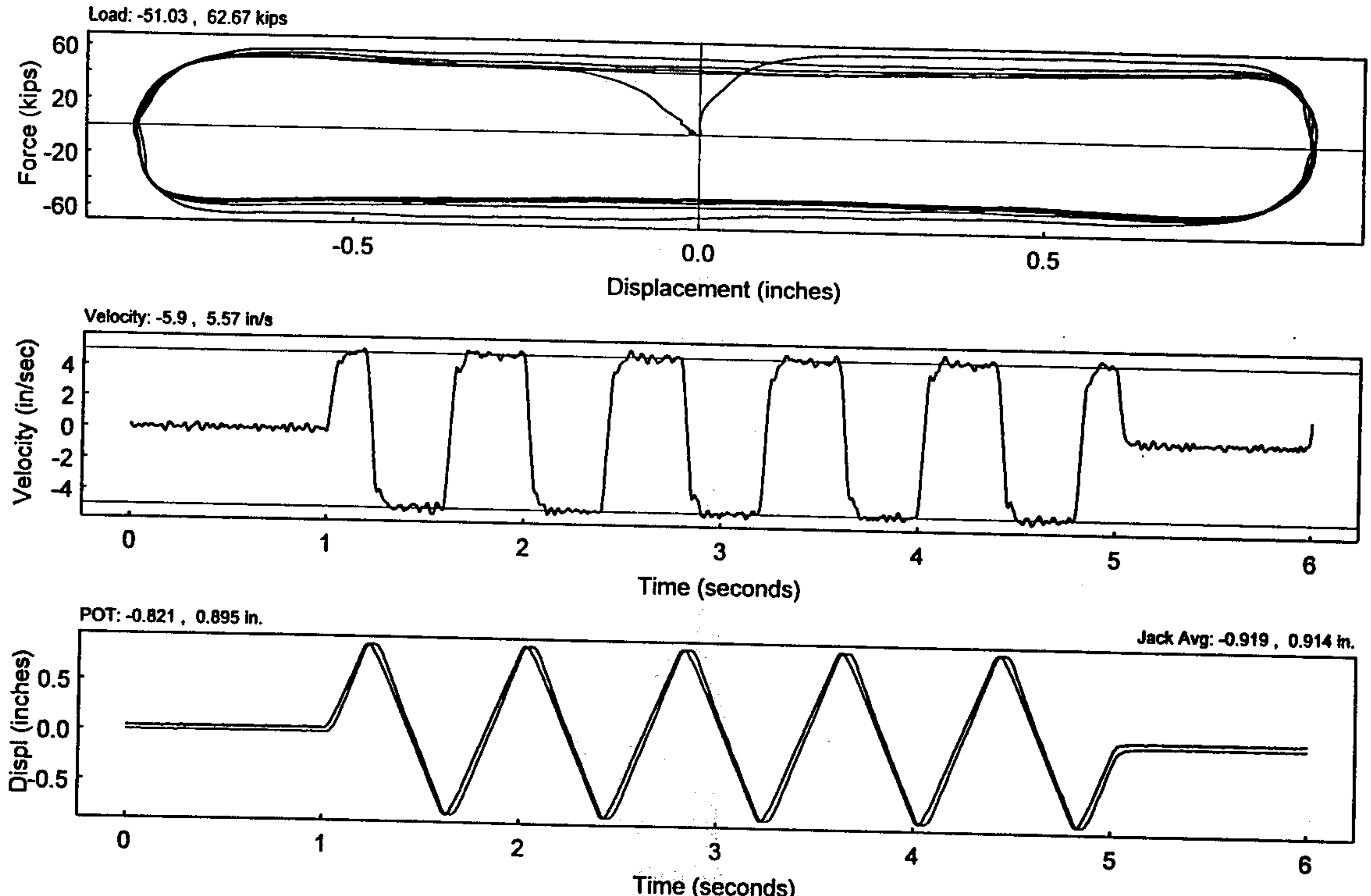
Damper: C

Test: sawi2
Target Velocity: 2 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 4 13:42:08 1995
Function: cvplot.s

File: 950504.02



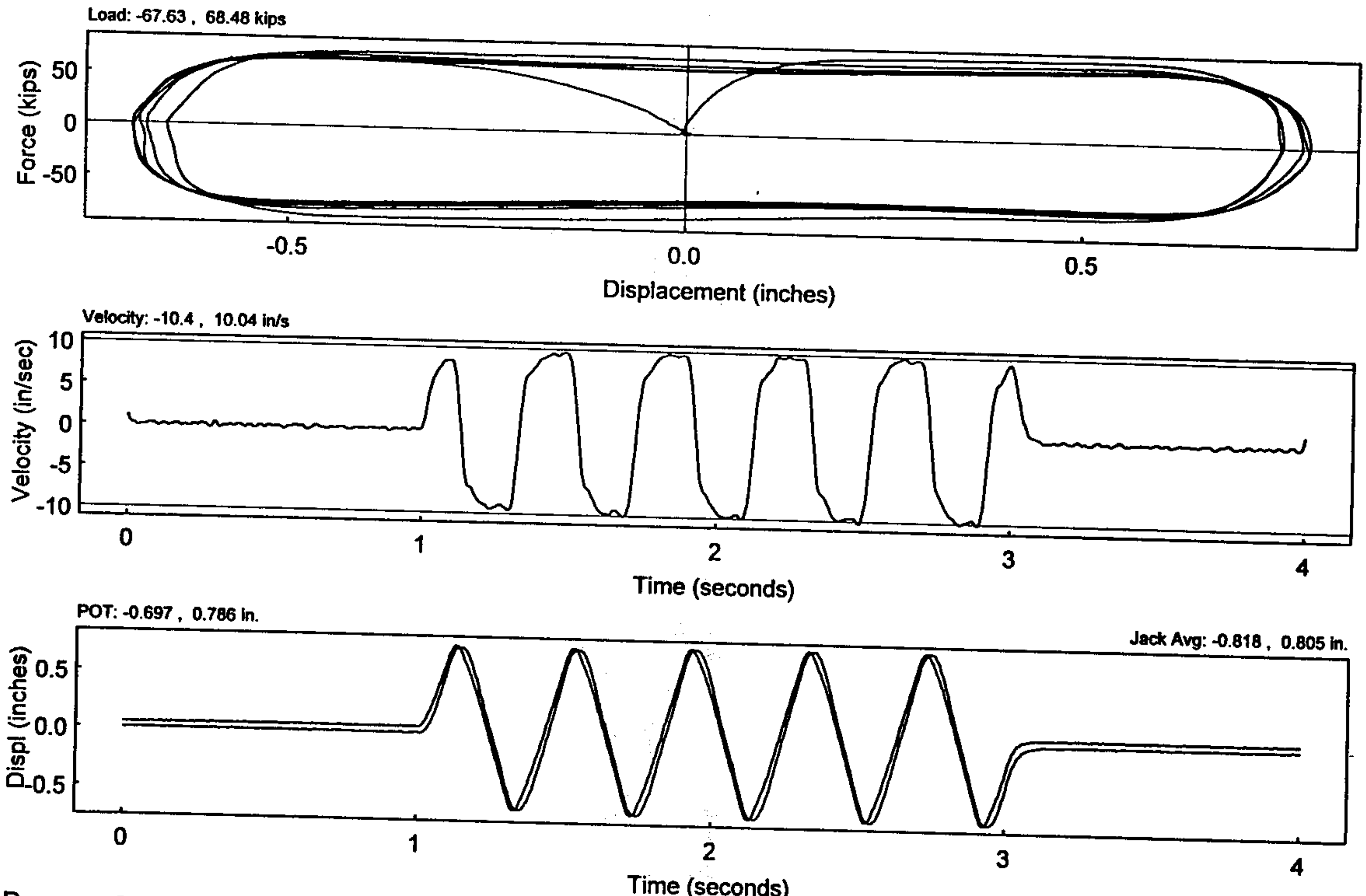
Damper: C

Test: sawi3
Target Velocity: 5 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 4 13:43:26 1995
Function: cvplot.s

File: 950504.03



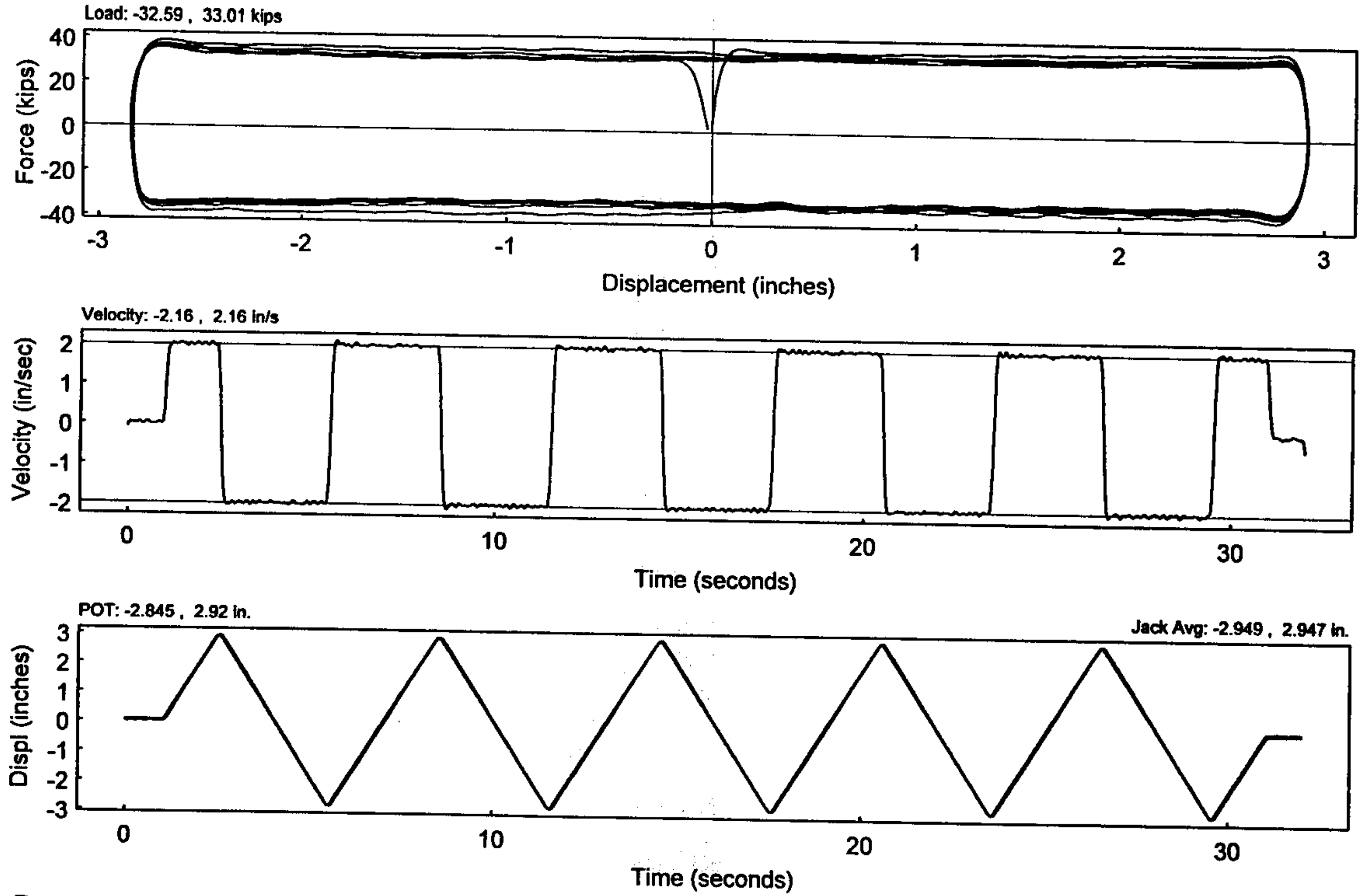
Damper: C

Test: sawi4
Target Velocity: 10 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 4 13:45:01 1995
Function: cvplot.s

File: 950504.04



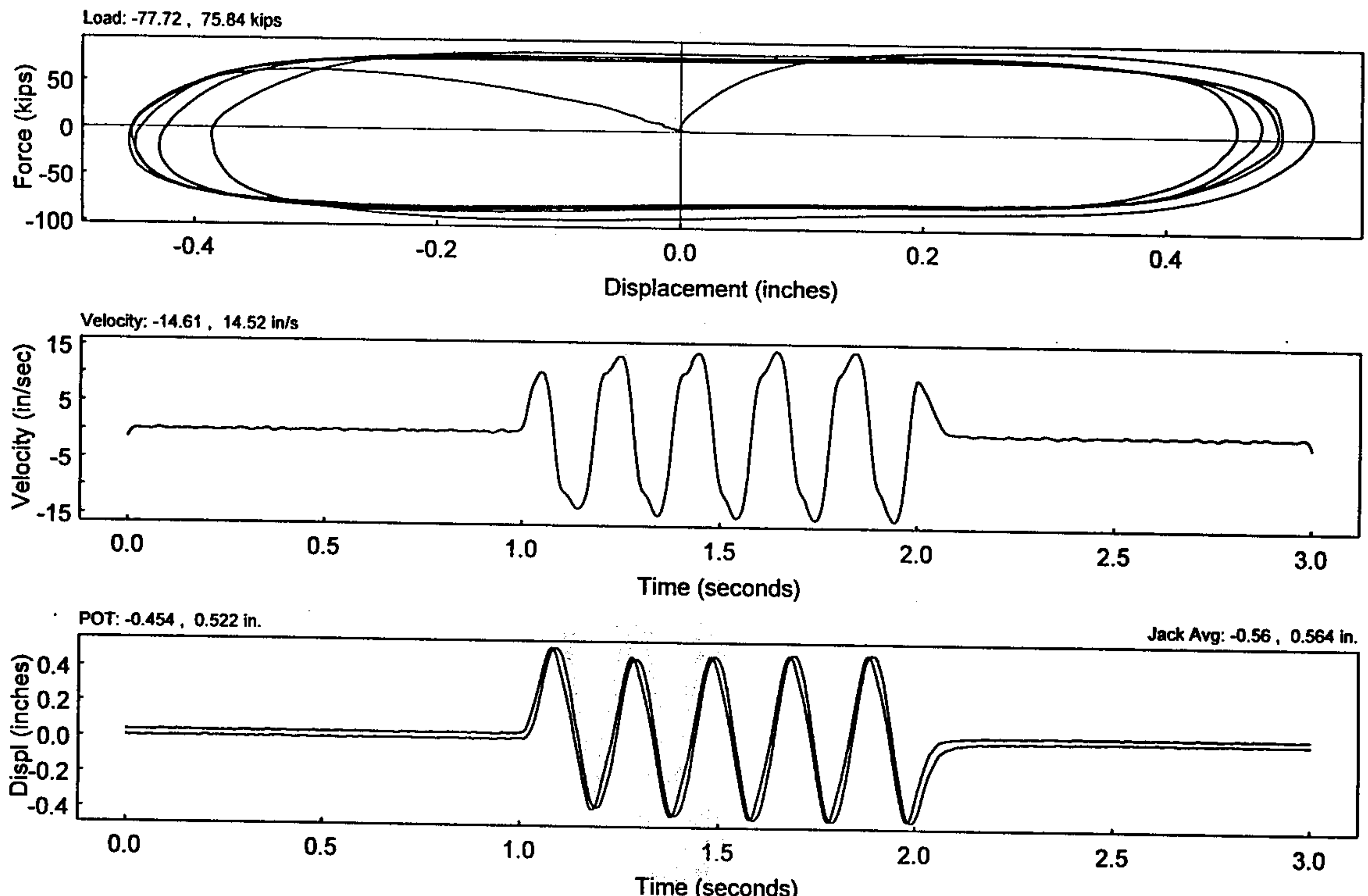
Damper: C

Test: sawi5
Target Velocity: 2 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 4 13:51:13 1995
Function: cvplot.s

File: 950504.05



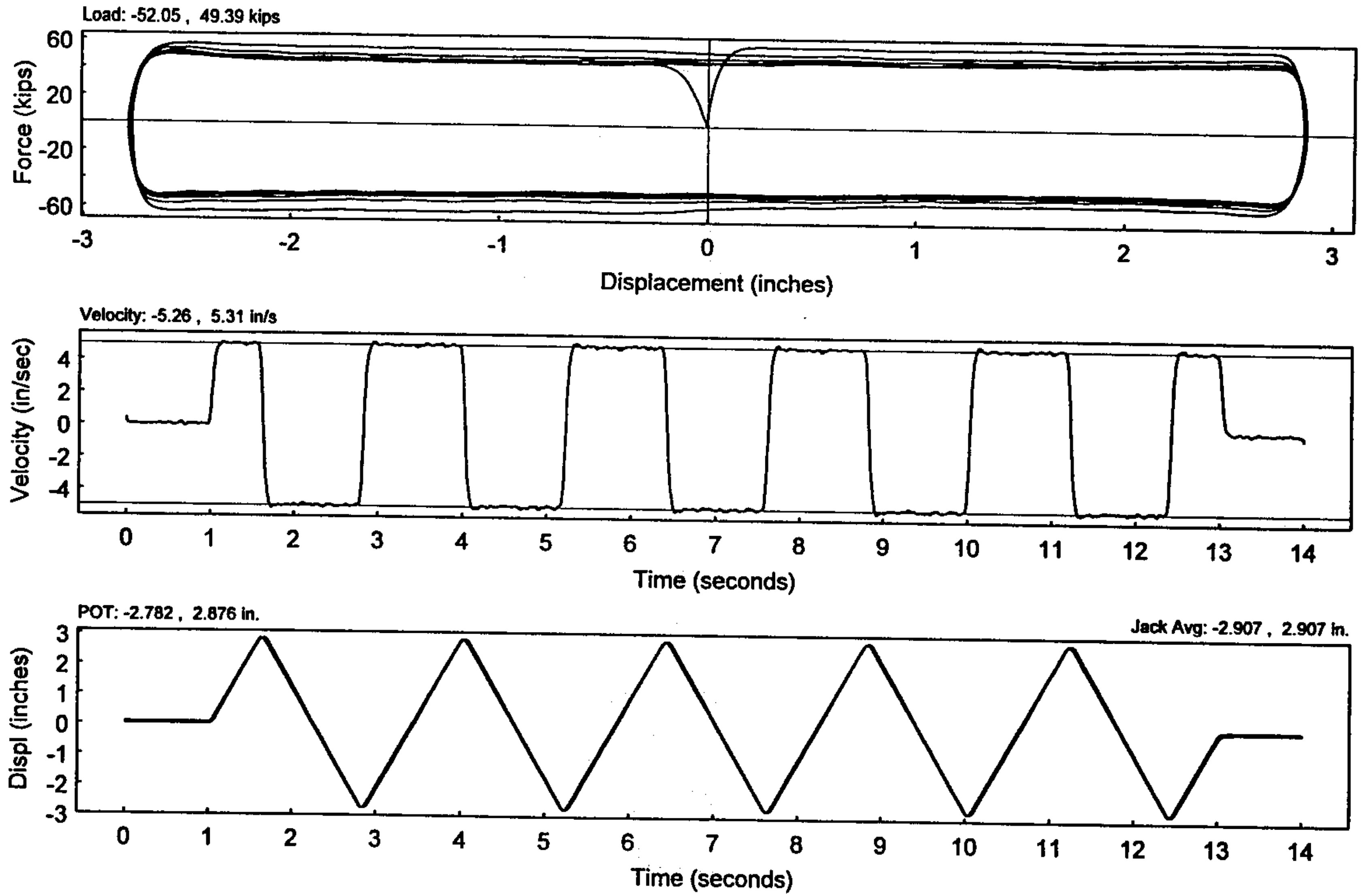
Damper: C

Test: sawi6
Target Velocity: 20 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Mon Dec 18 11:14:03 1995
Function: cvplot.s

File: 950504.06



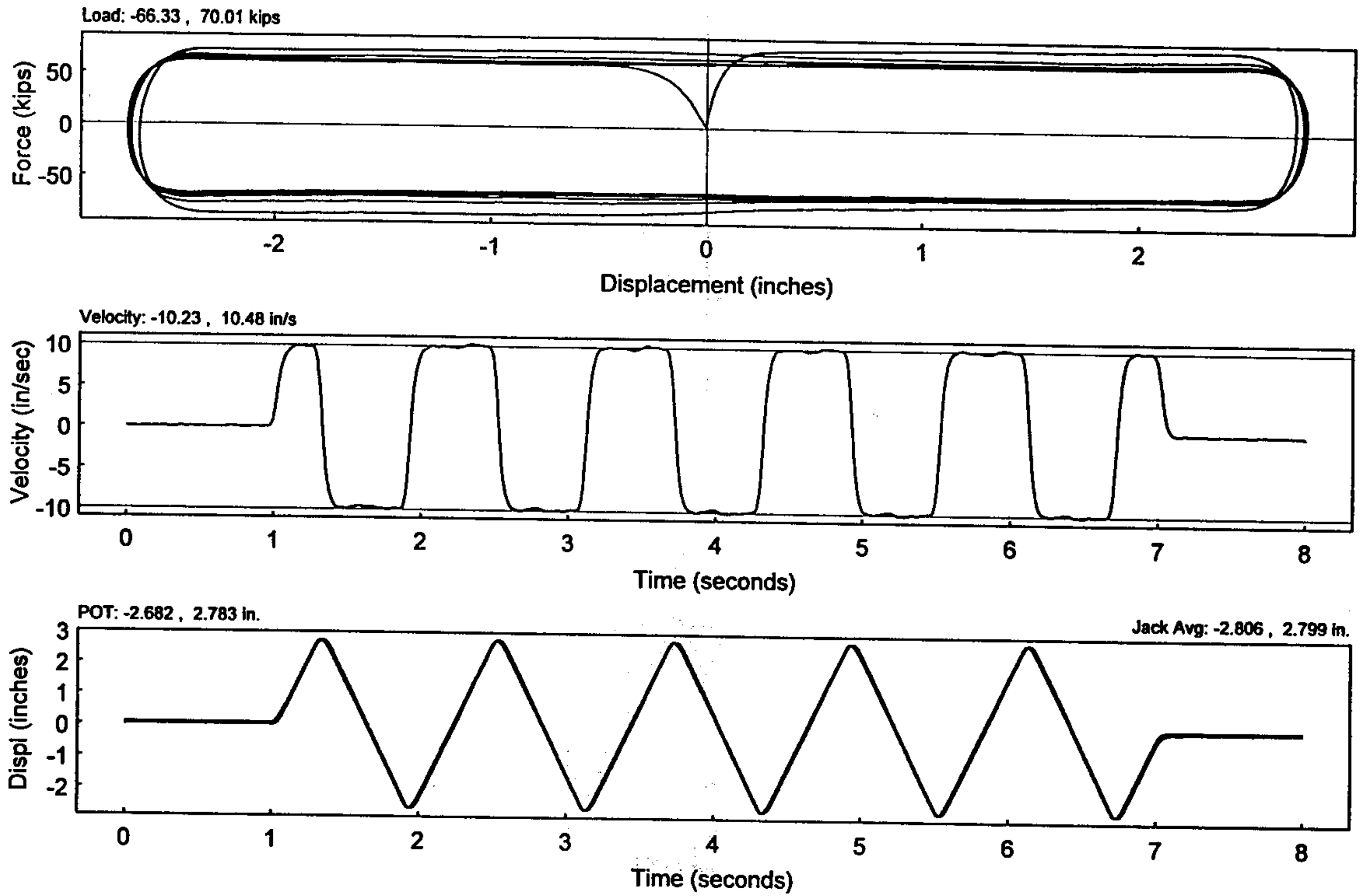
Damper: C

Test: sawi7
Target Velocity: 5 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 4 13:53:36 1995
Function: cvplot.s

File: 950504.07



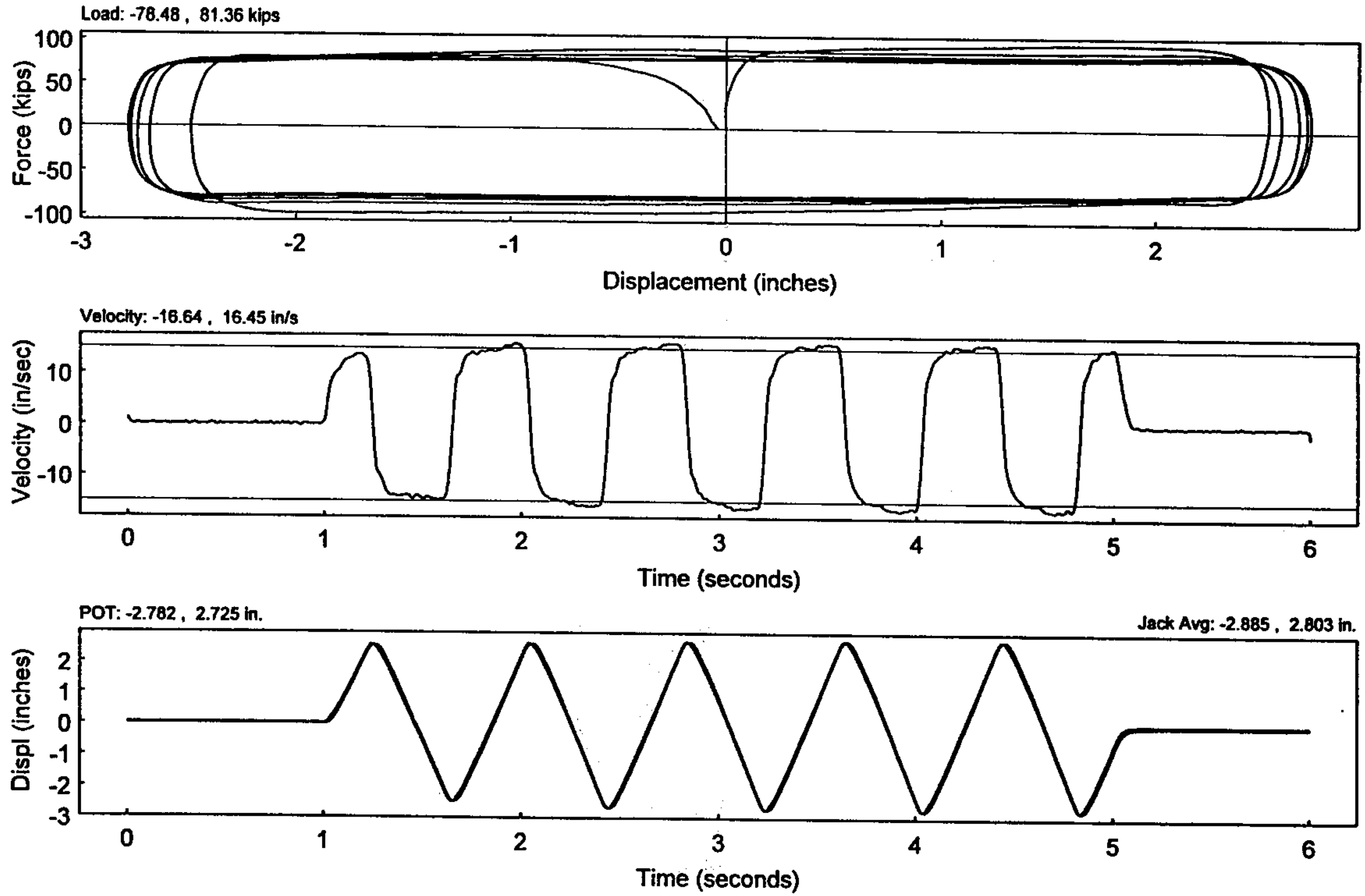
Damper: C

Test: sawi8
Target Velocity: 10 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 4 13:54:49 1995
Function: cvplot.s

File: 950504.08



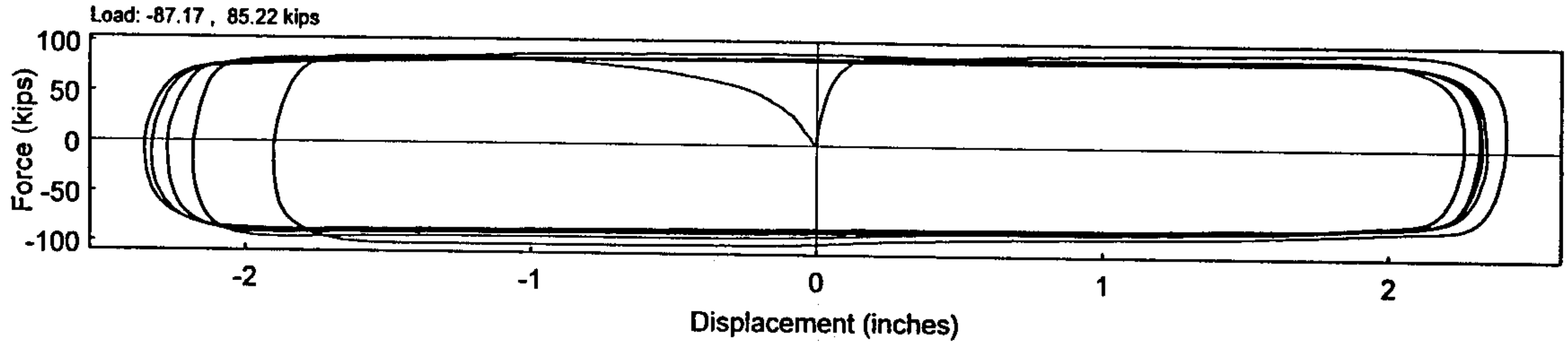
Damper: C

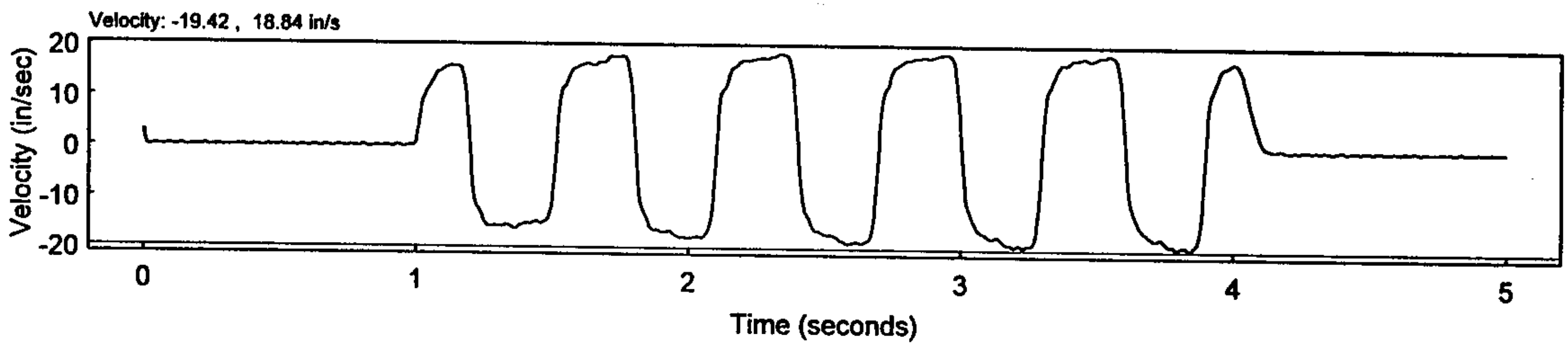
Test: sawi9
Target Velocity: 15 in/sec

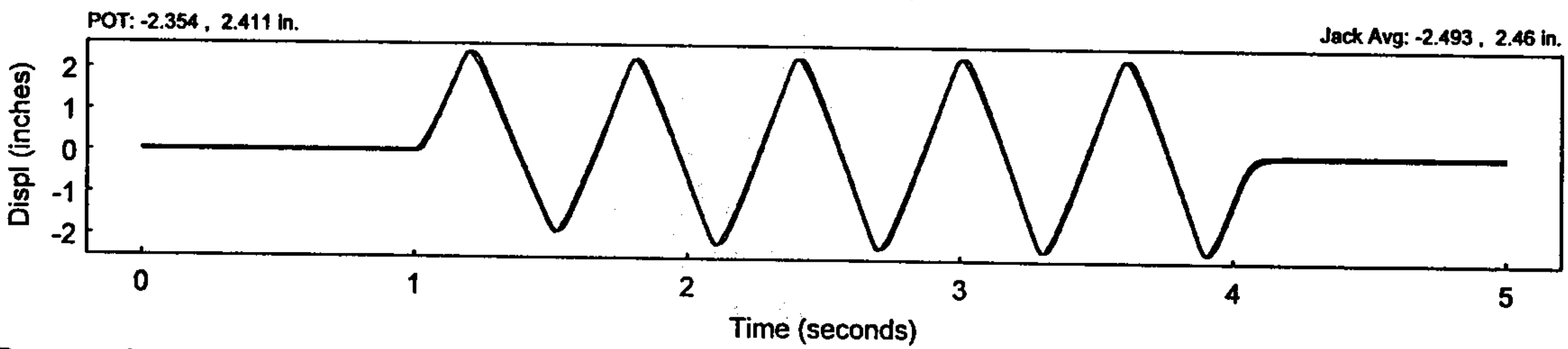
Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 4 20:06:15 1995
Function: cvplot.s

File: 950504.09







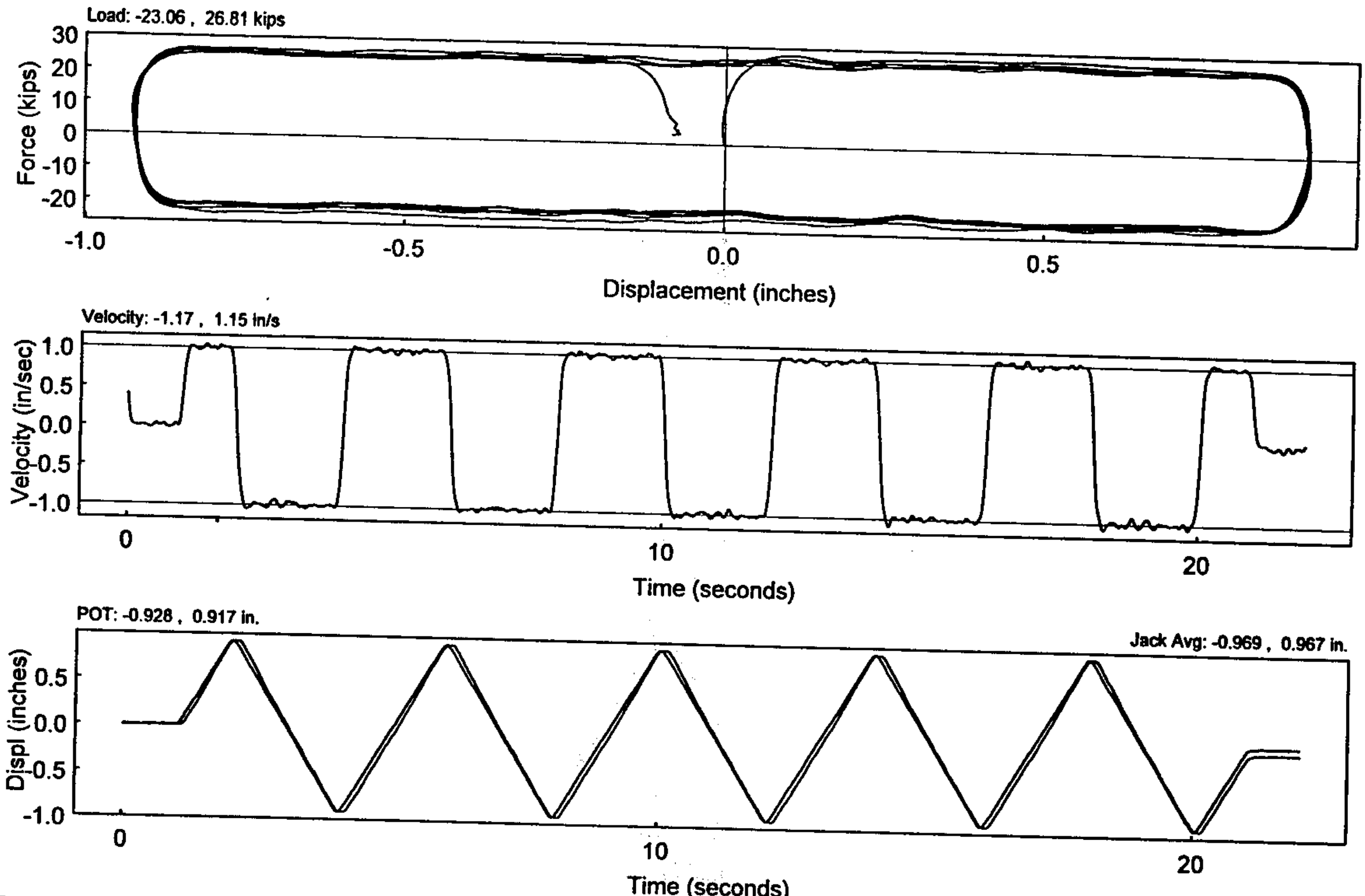
Damper: C

Test: sawi10
Target Velocity: 20 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 4 20:07:20 1995
Function: cvplot.s

File: 950504.10



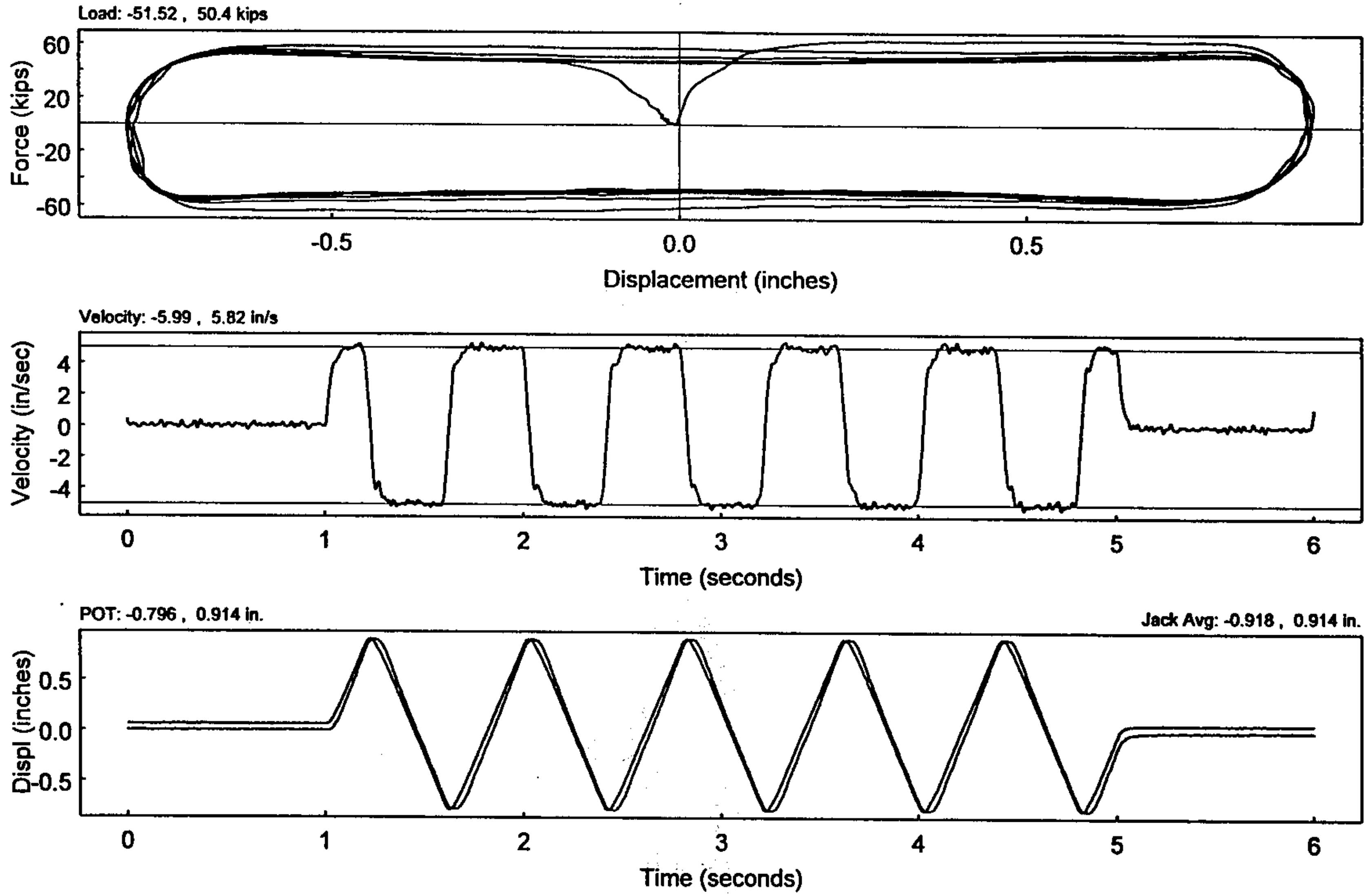
Damper: C

Test: sawc1
Target Velocity: 1 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 11 23:12:16 1995
Function: cvplot.s

File: 950511.01



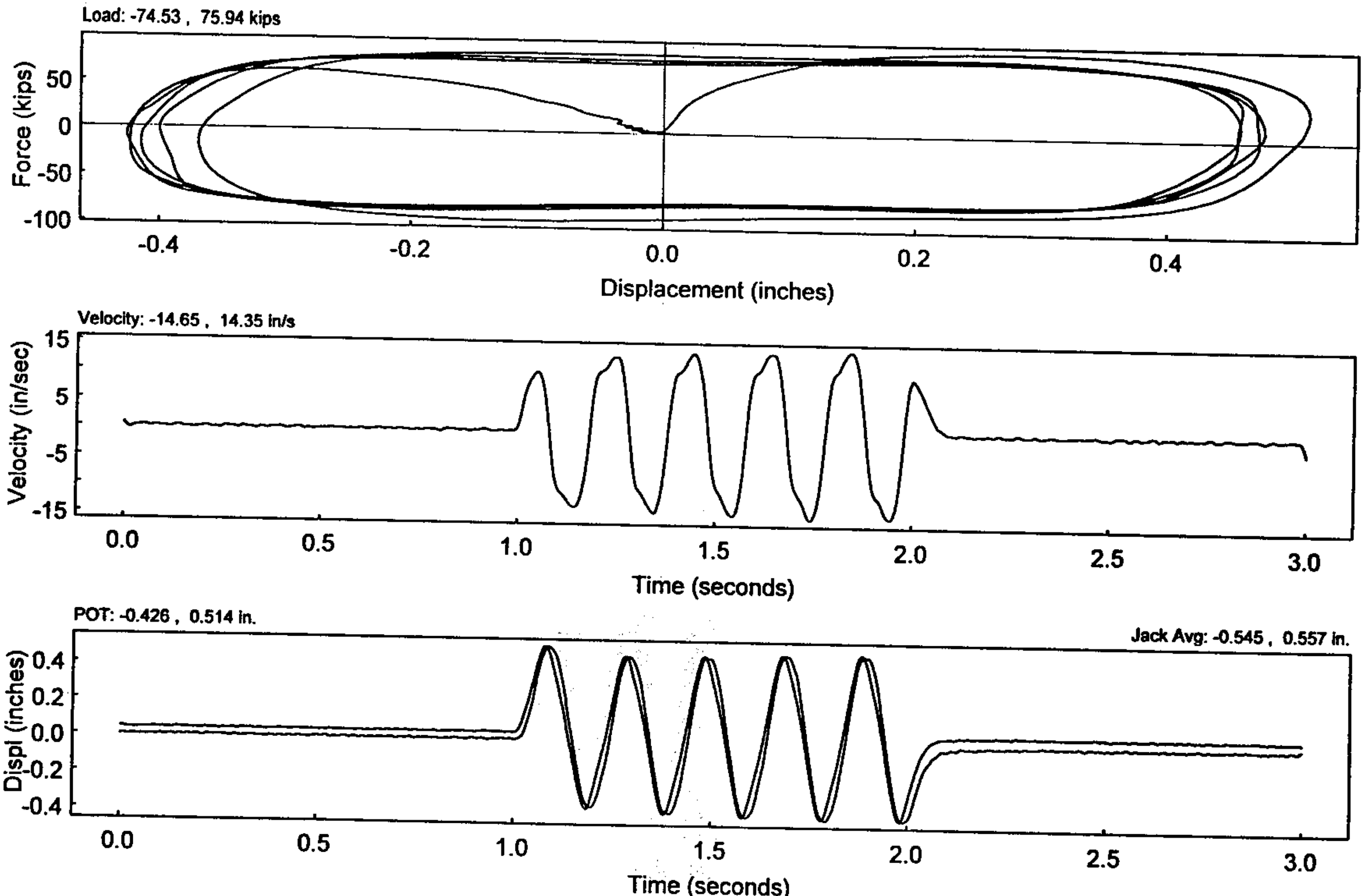
Damper: C

Test: sawc2
Target Velocity: 5 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 11 23:13:25 1995
Function: cvplot.s

File: 950511.02



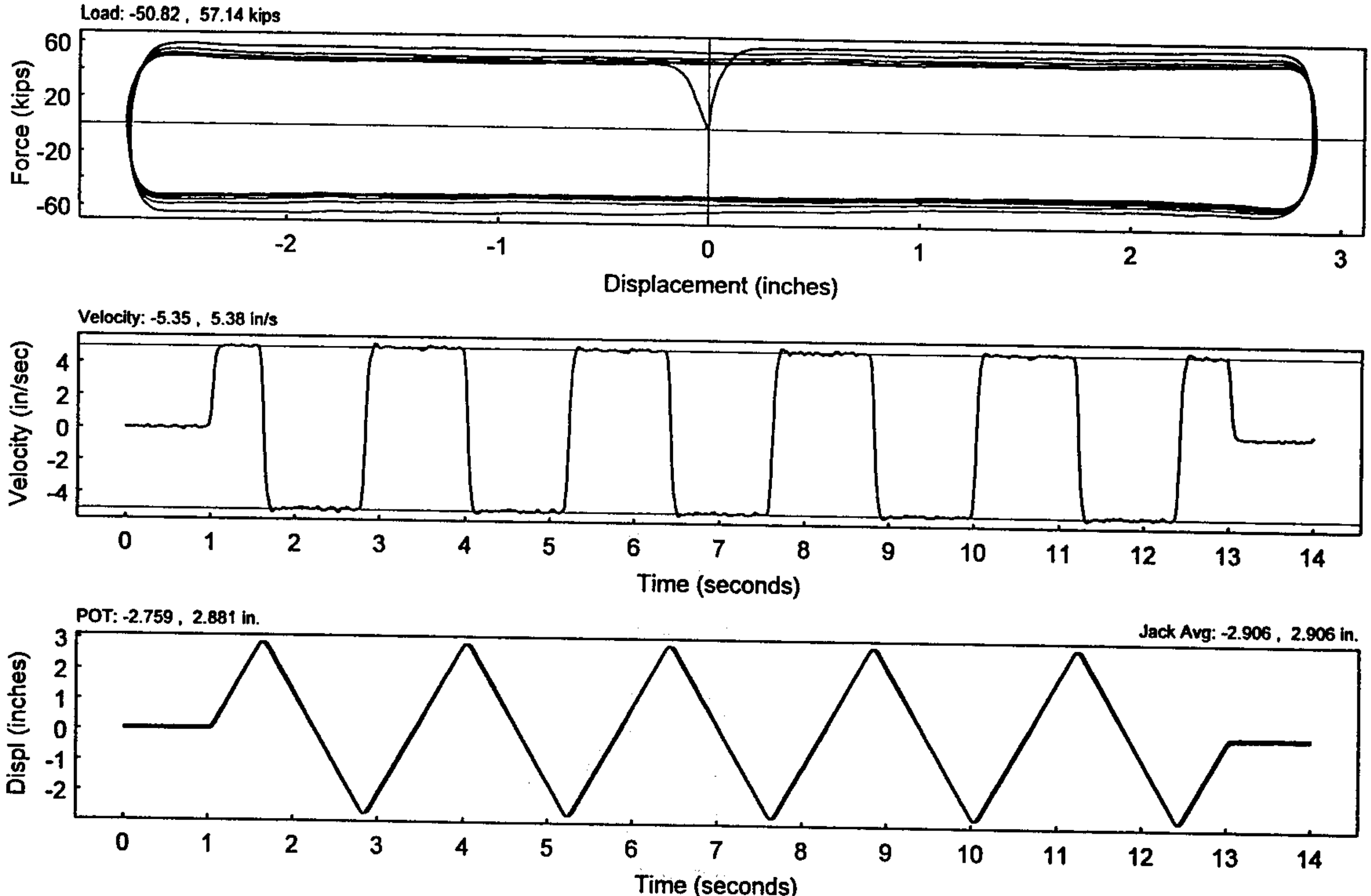
Damper: C

Test: sawc3
Target Velocity: 20 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Mon Dec 18 11:16:45 1995
Function: cvplot.s

File: 950511.03



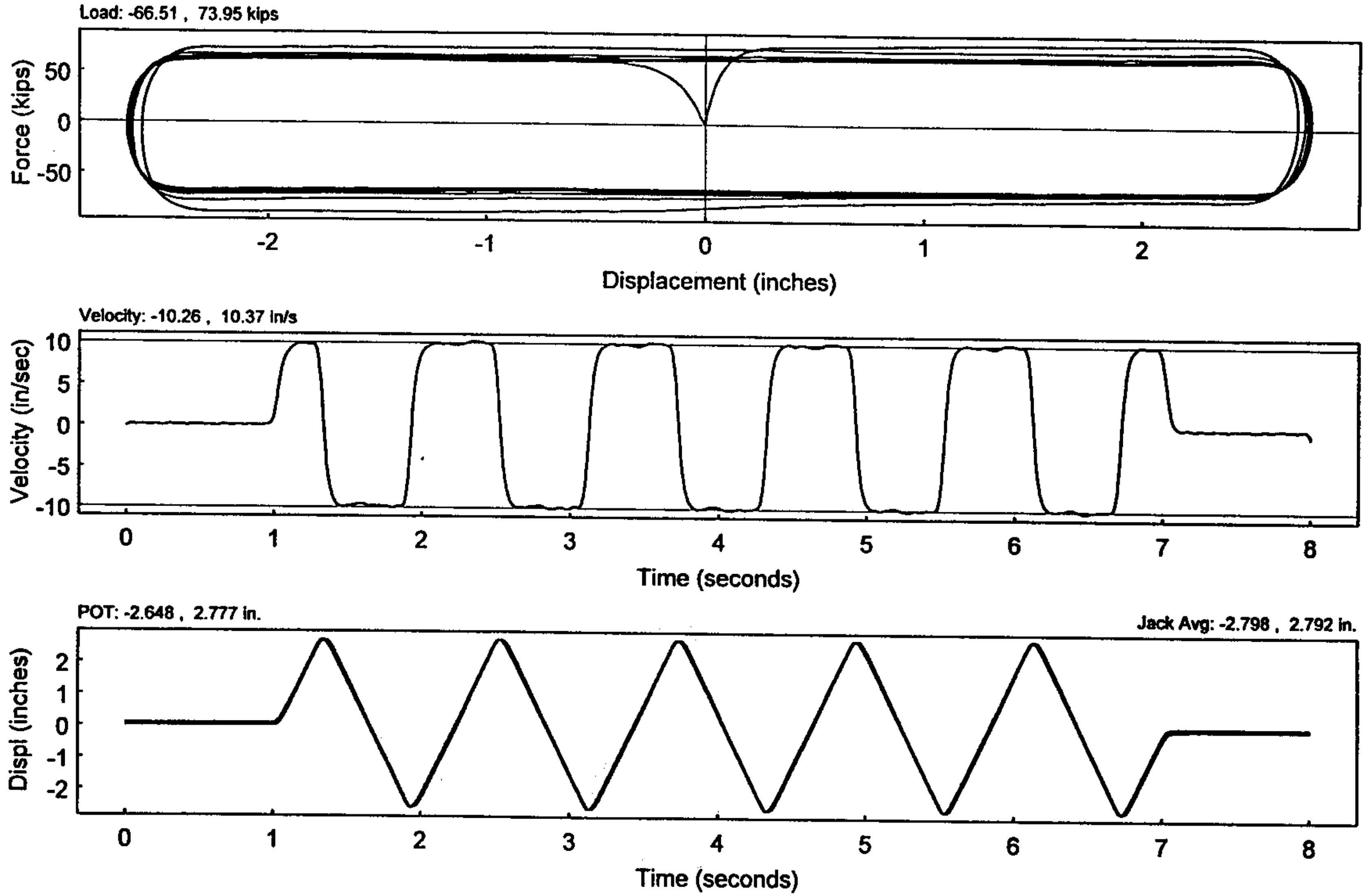
Damper: C

Test: sawc4
Target Velocity: 5 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 11 23:17:07 1995
Function: cvplot.s

File: 950511.04



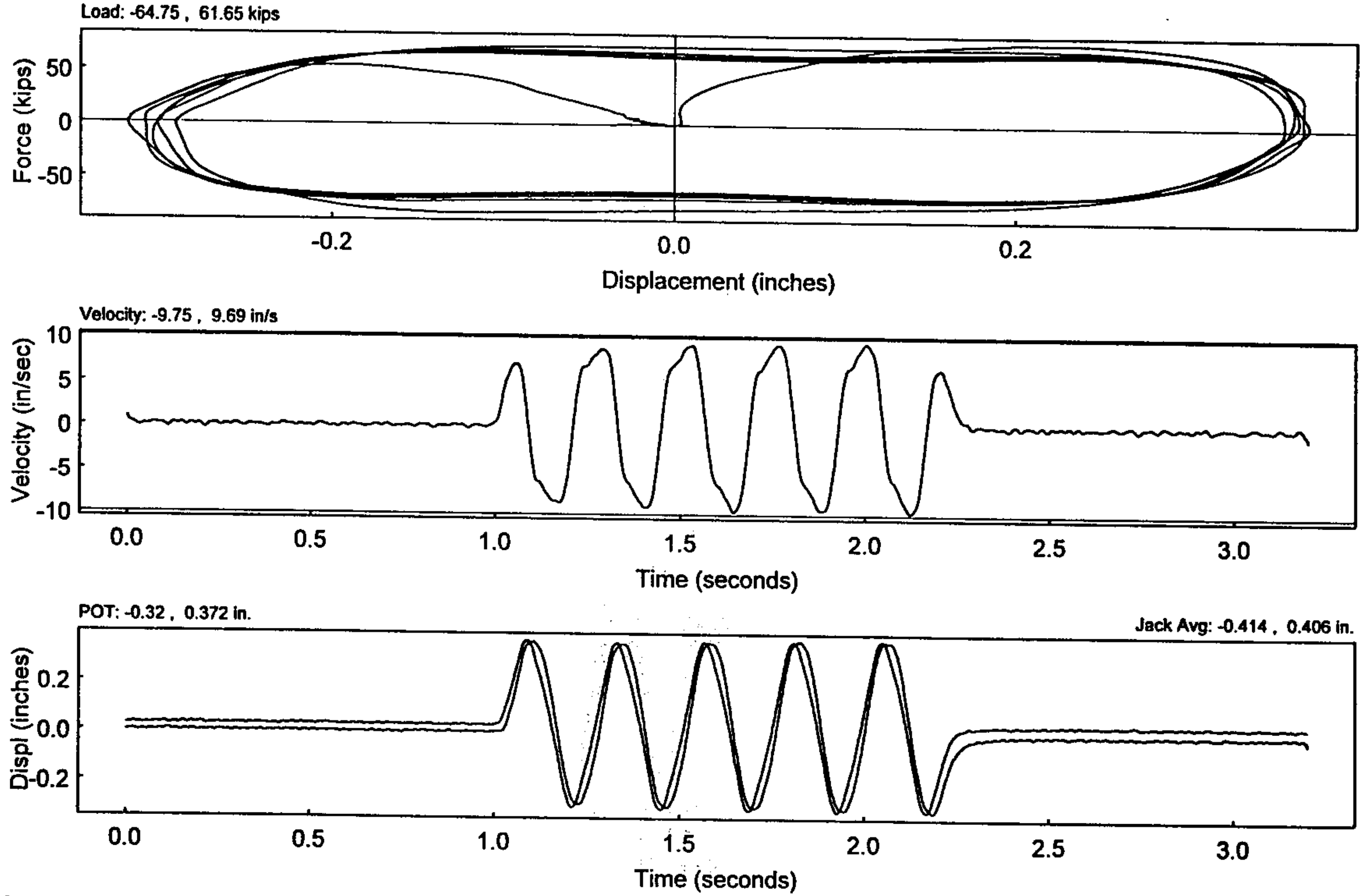
Damper: C

Test: sawc5
Target Velocity: 10 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 11 23:18:00 1995
Function: cvplot.s

File: 950511.05



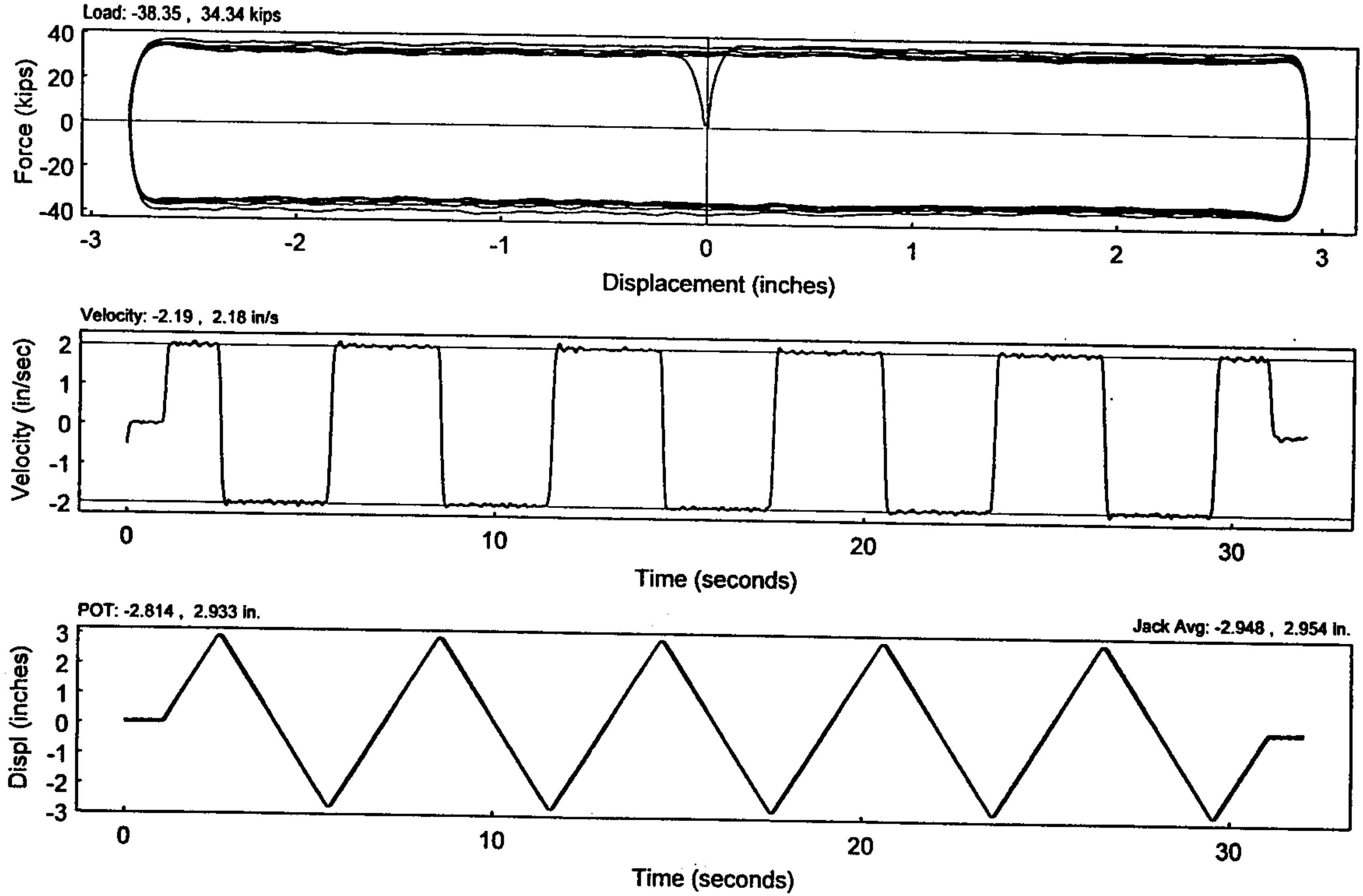
Damper: C

Test: sawc7
Target Velocity: 10 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Mon Dec 18 11:18:44 1995
Function: cvplot.s

File: 950511.06



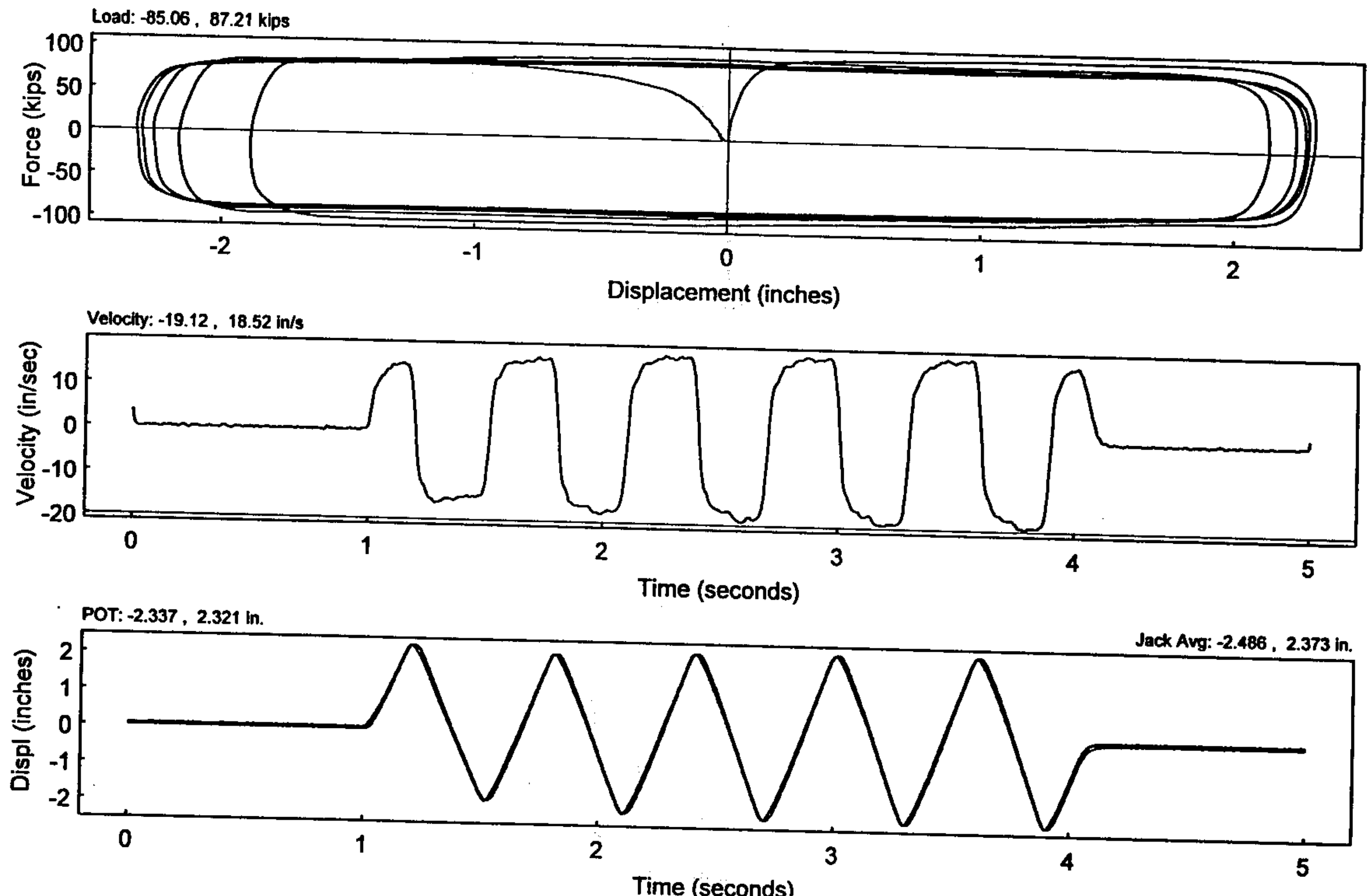
Damper: C

Test: sawc8
Target Velocity: 2 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 11 23:20:22 1995
Function: cvplot.s

File: 950511.07



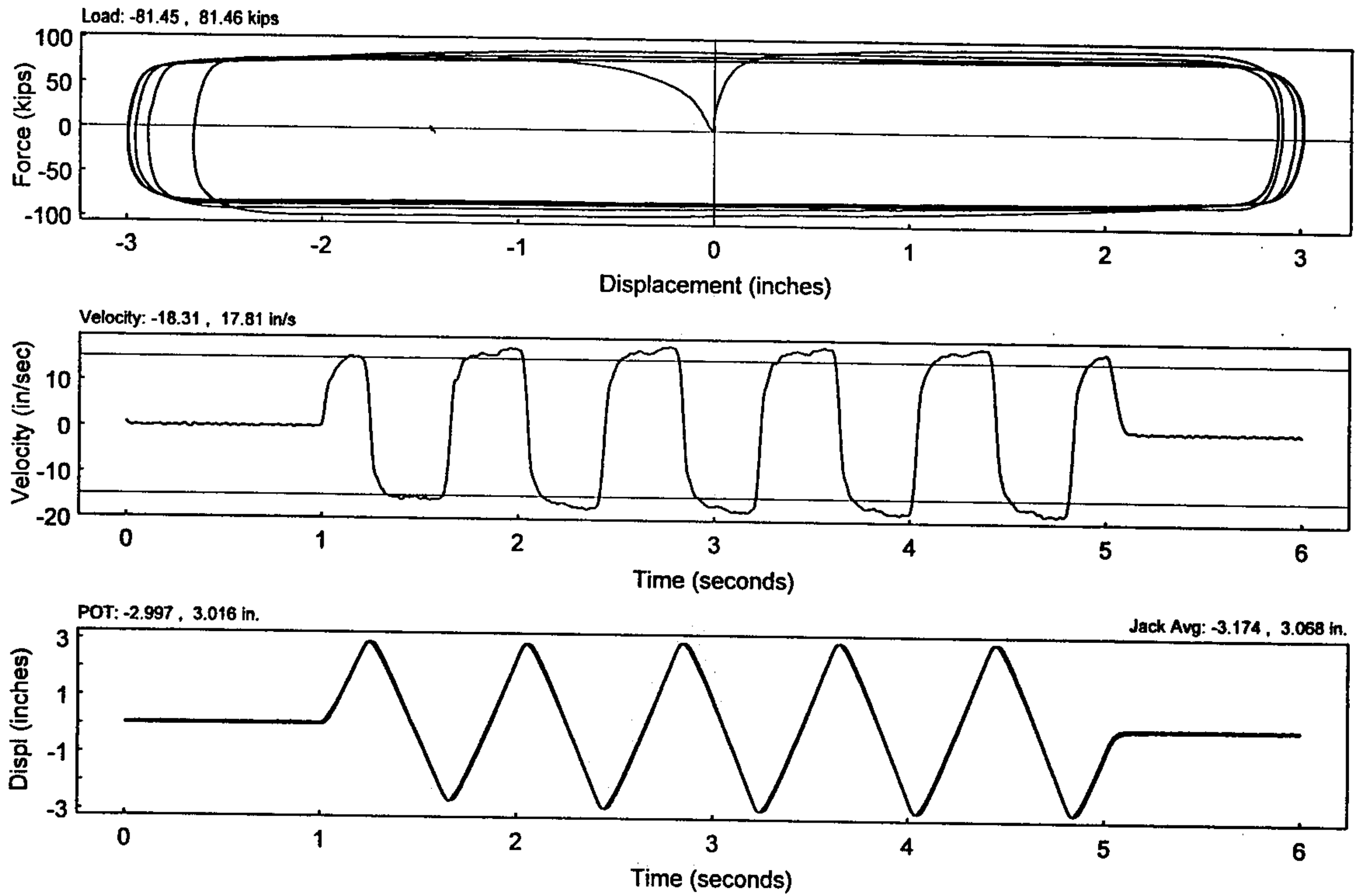
Damper: C

Test: sawc9
Target Velocity: 20 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 11 23:21:18 1995
Function: cvplot.s

File: 950511.08



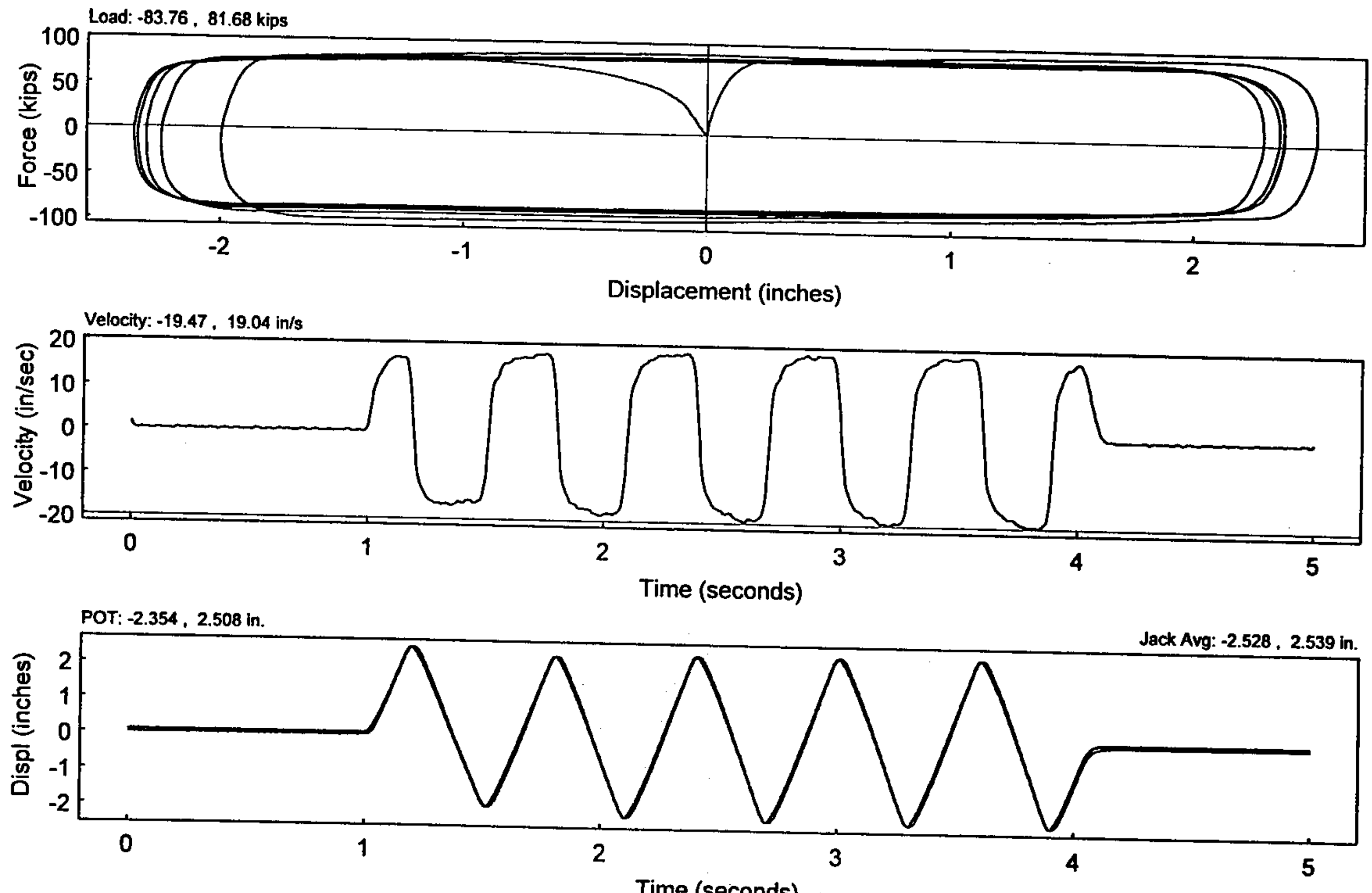
Damper: C

Test: sawc14
Target Velocity: 15 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 20:52:15 1995
Function: cvplot.s

File: 950512.17



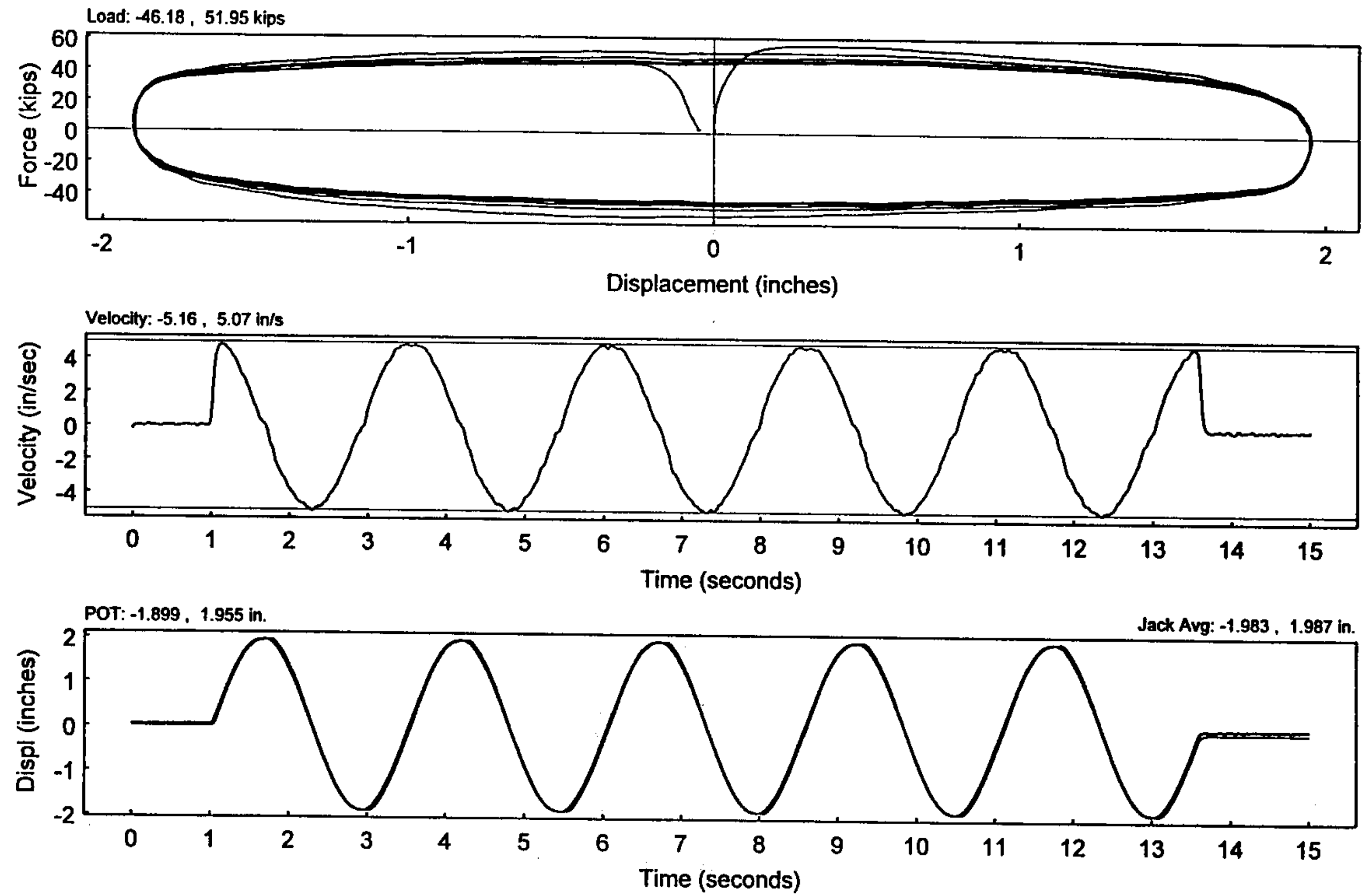
Damper: C

Test: sawc9
Target Velocity: 20 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 20:53:21 1995
Function: cvplot.s

File: 950512.18



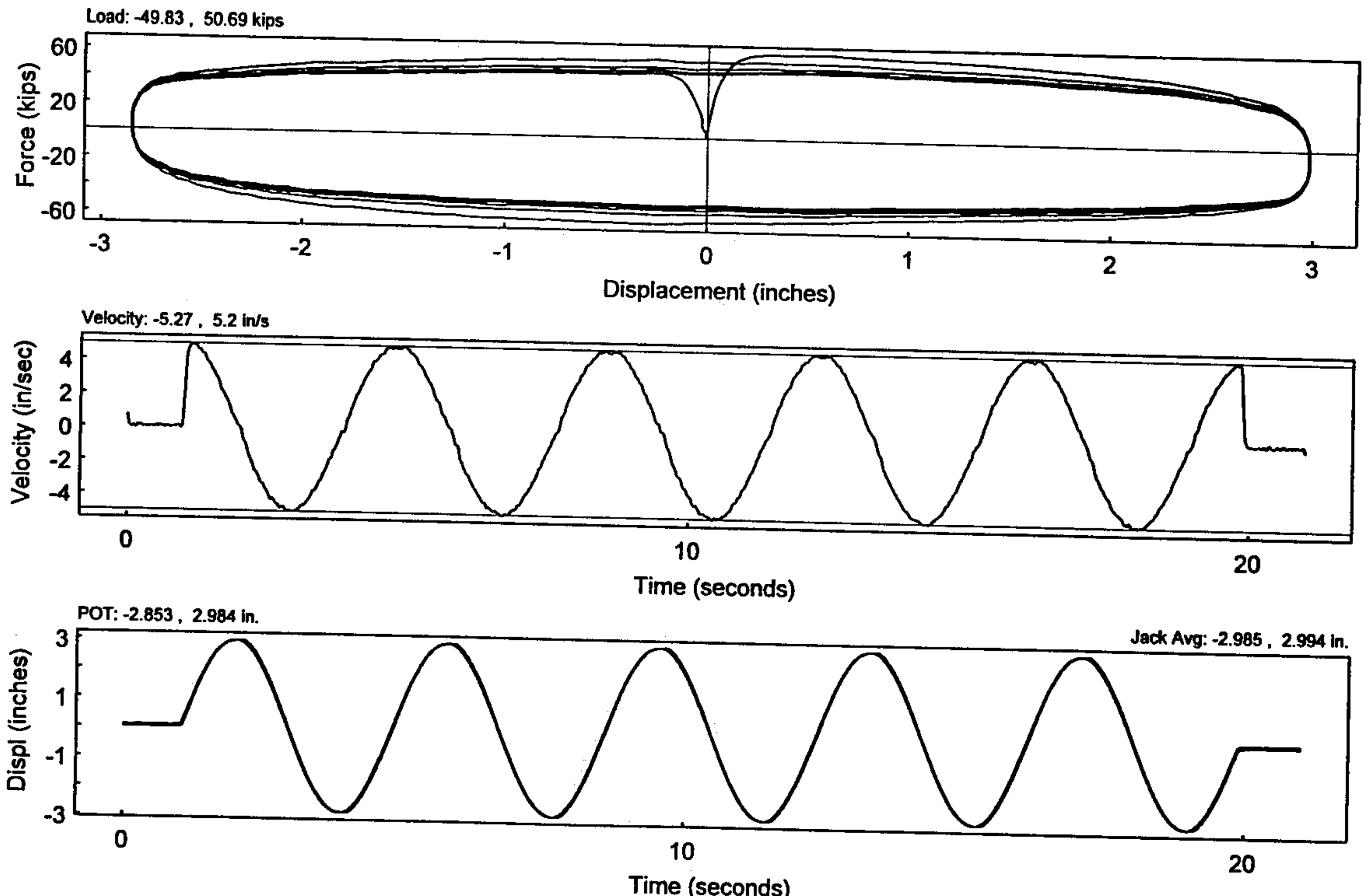
Damper: C

Test: sinc18
Target Velocity: 5 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 20:56:56 1995
Function: cvplot.s

File: 950512.19



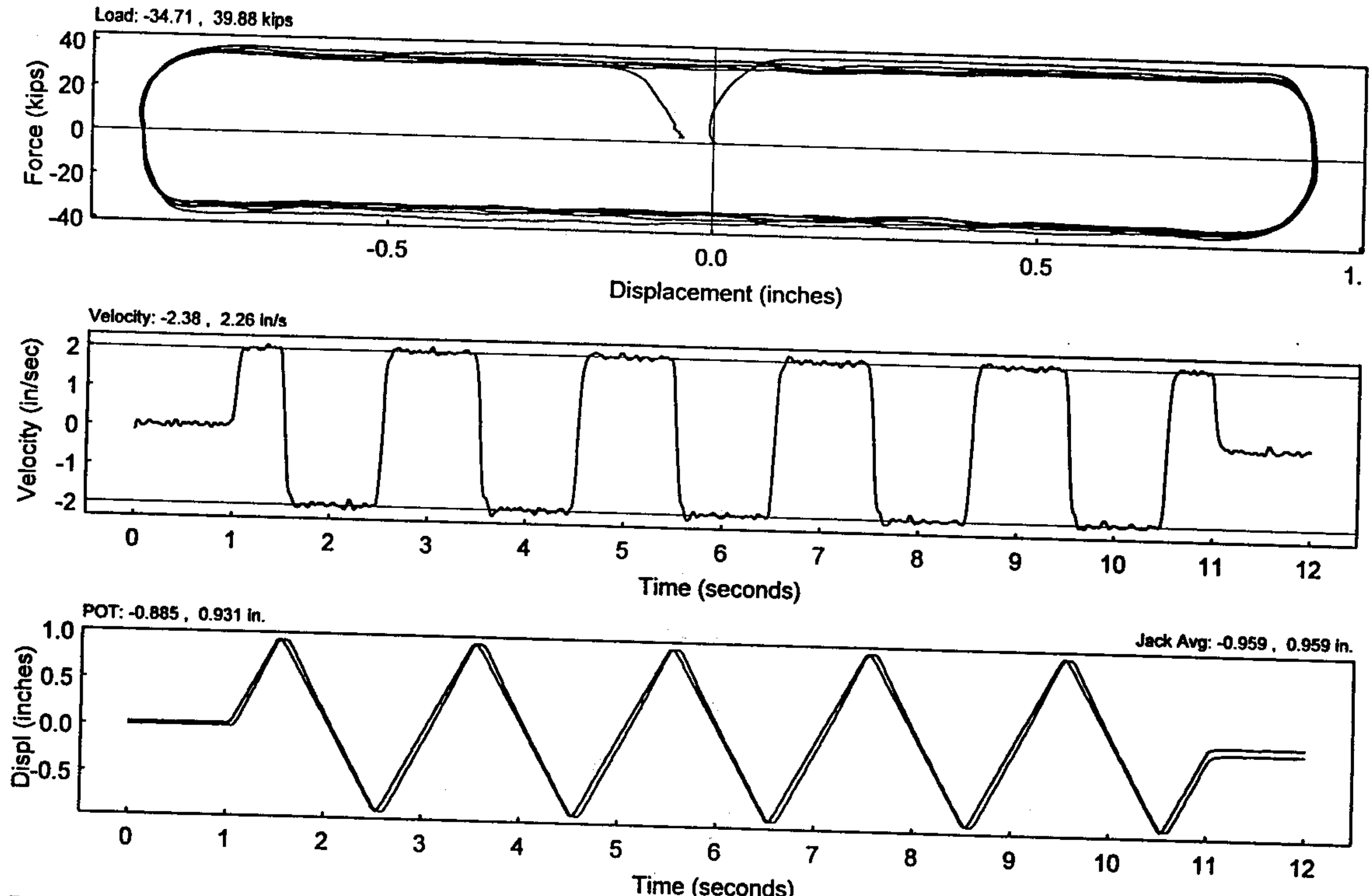
Damper: C

Test: sinc10
Target Velocity: 5 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 11 23:22:17 1995
Function: cvplot.s

File: 950511.11



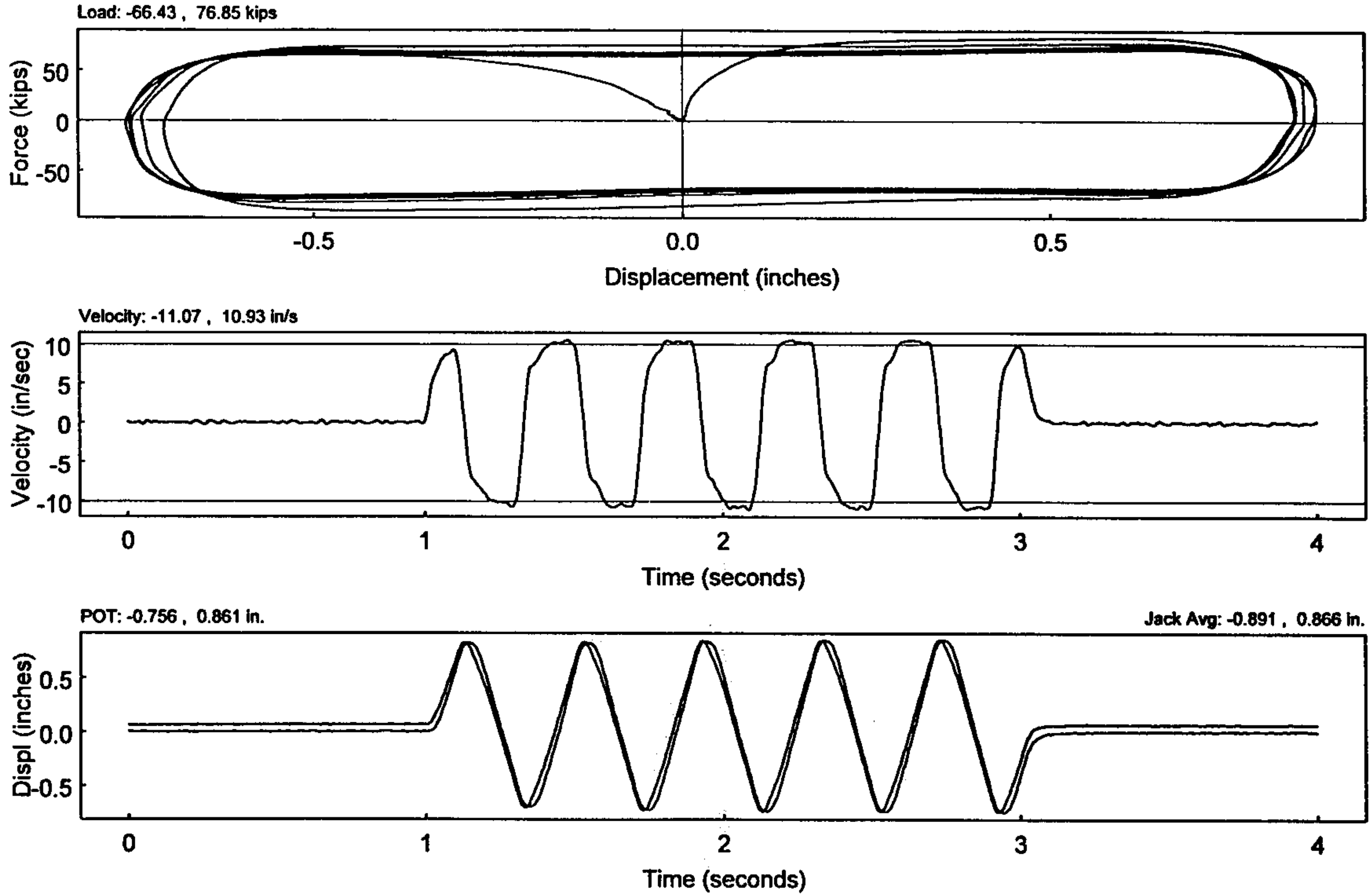
Damper: C

Test: sawc12
Target Velocity: 2 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 11 23:36:15 1995
Function: cvplot.s

File: 950511.13



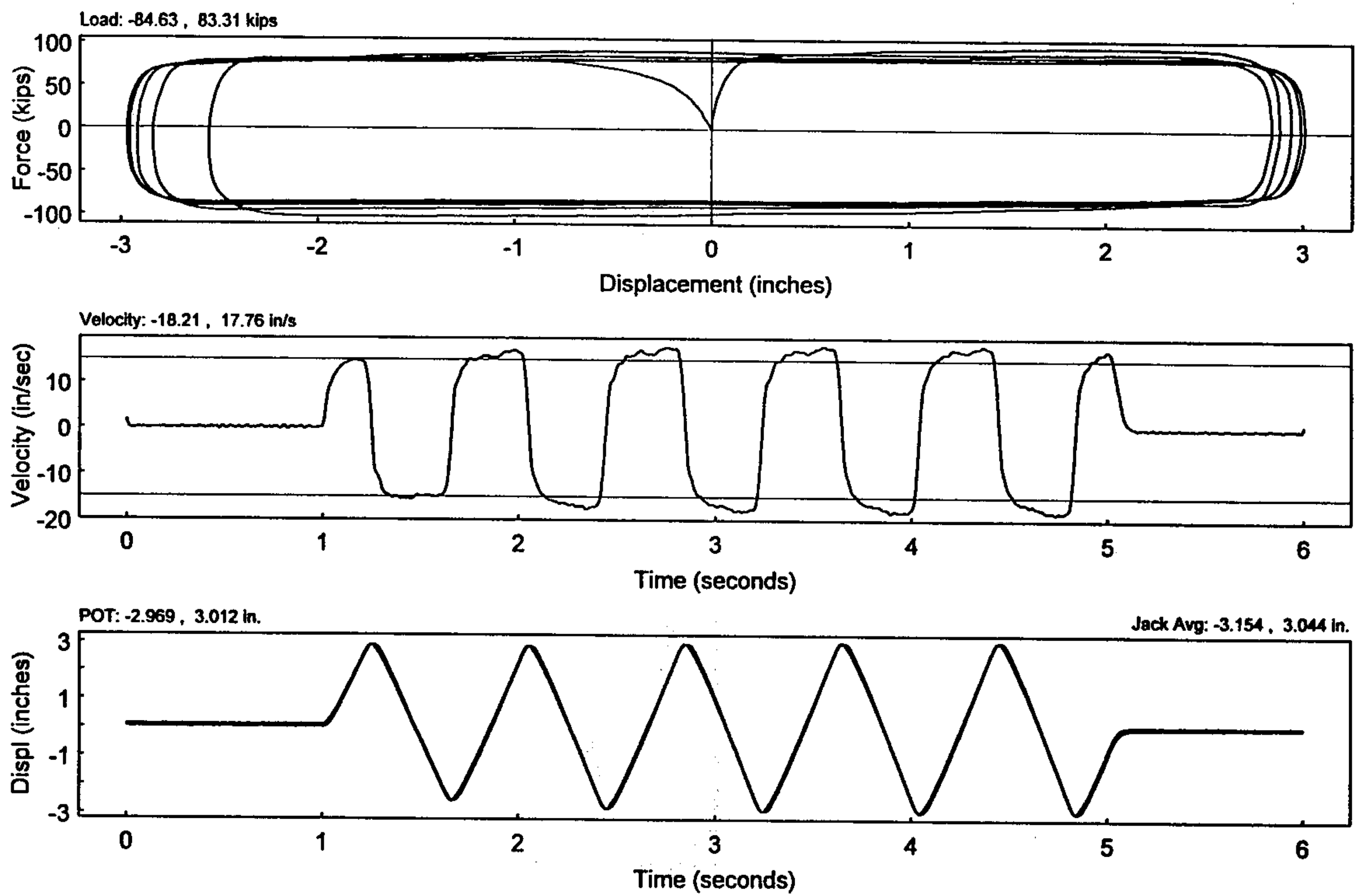
Damper: C

Test: sawc13
Target Velocity: 10 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 11 23:37:11 1995
Function: cvplot.s

File: 950511.14



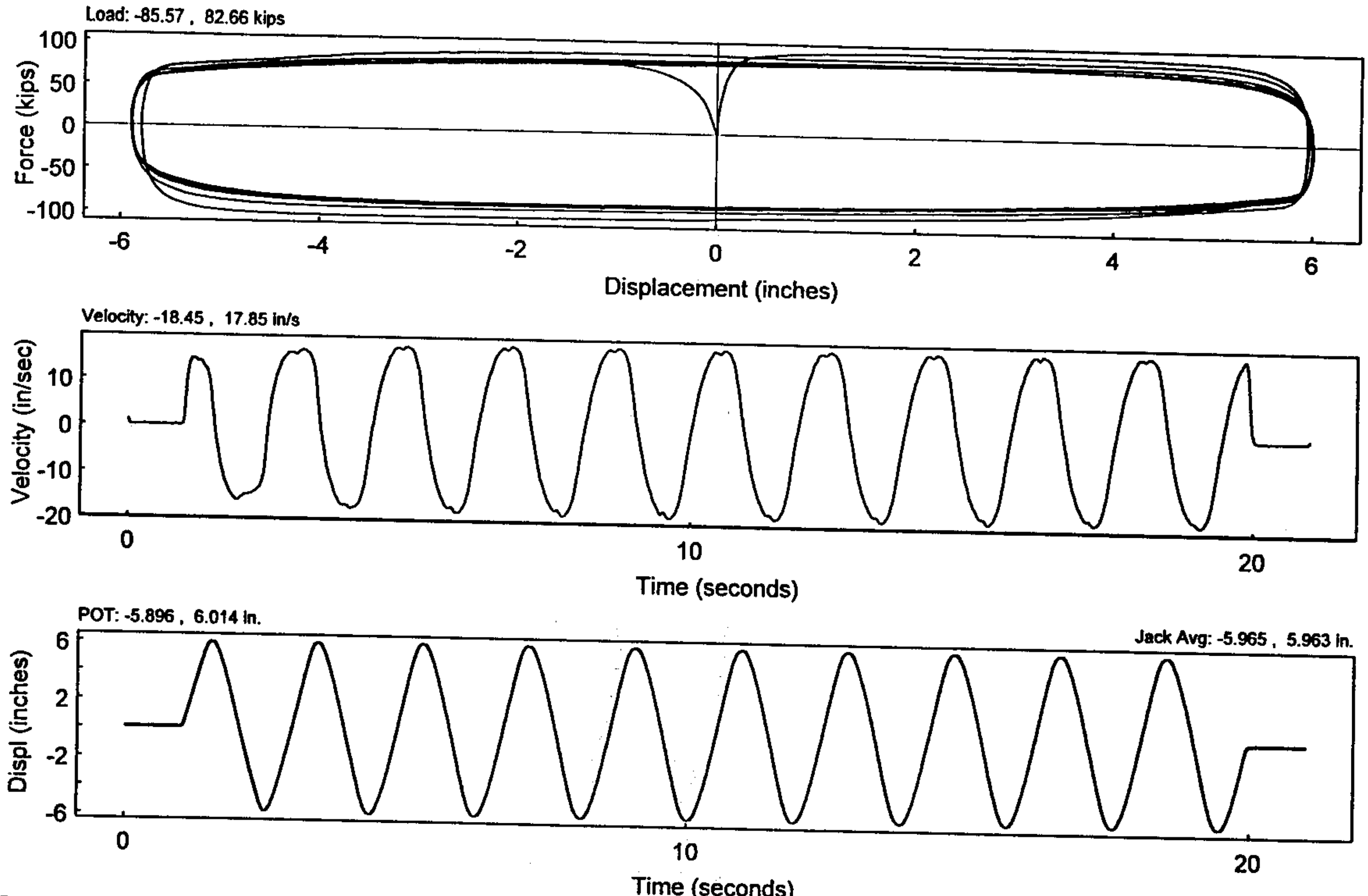
Damper: C

Test: sawc14
Target Velocity: 15 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Thu May 11 23:38:13 1995
Function: cvplot.s

File: 950511.15



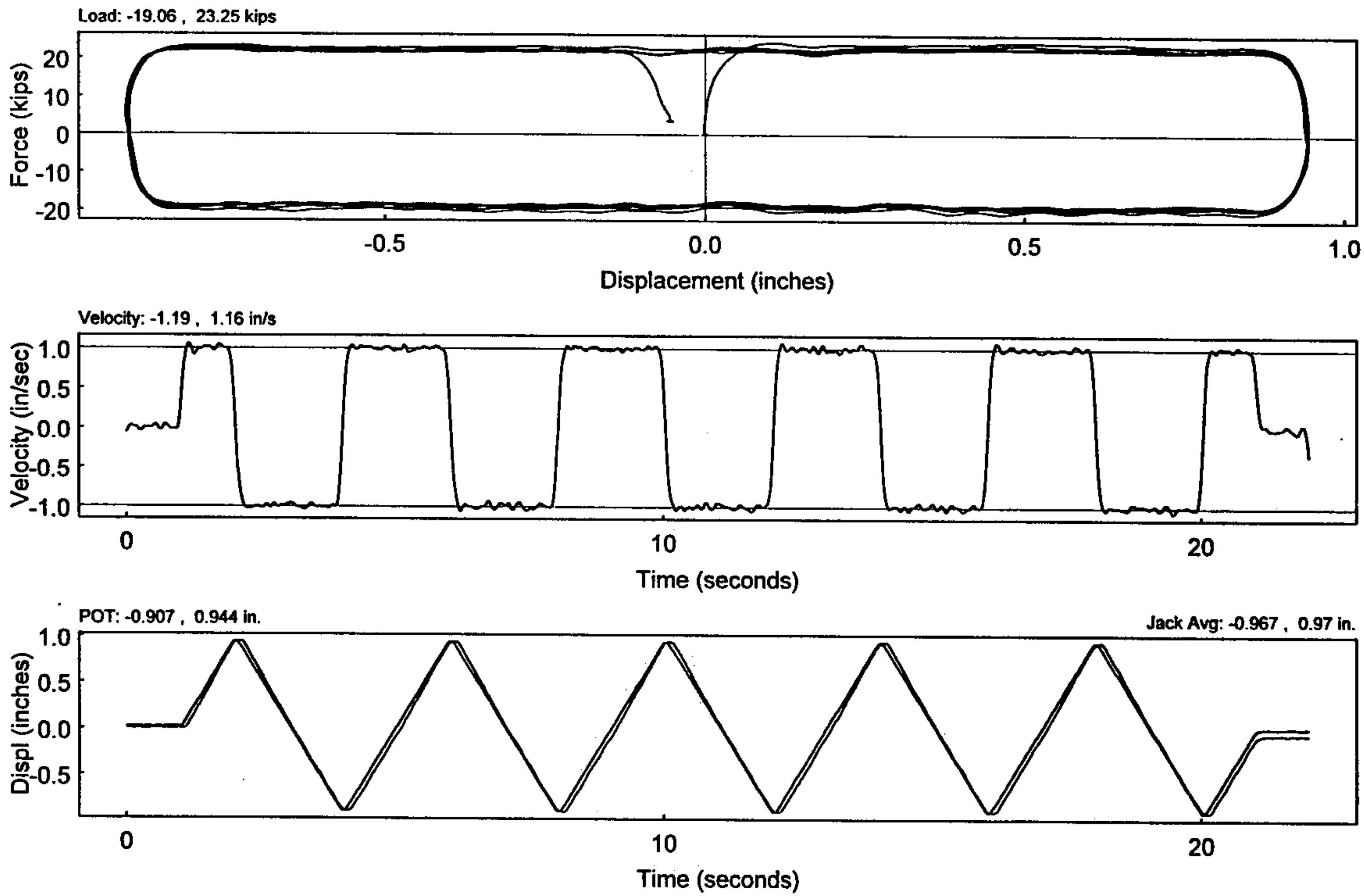
Damper: C

Test: sinc15
Target Velocity: 20 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 21:01:53 1995
Function: cvplot.s

File: 950511.16



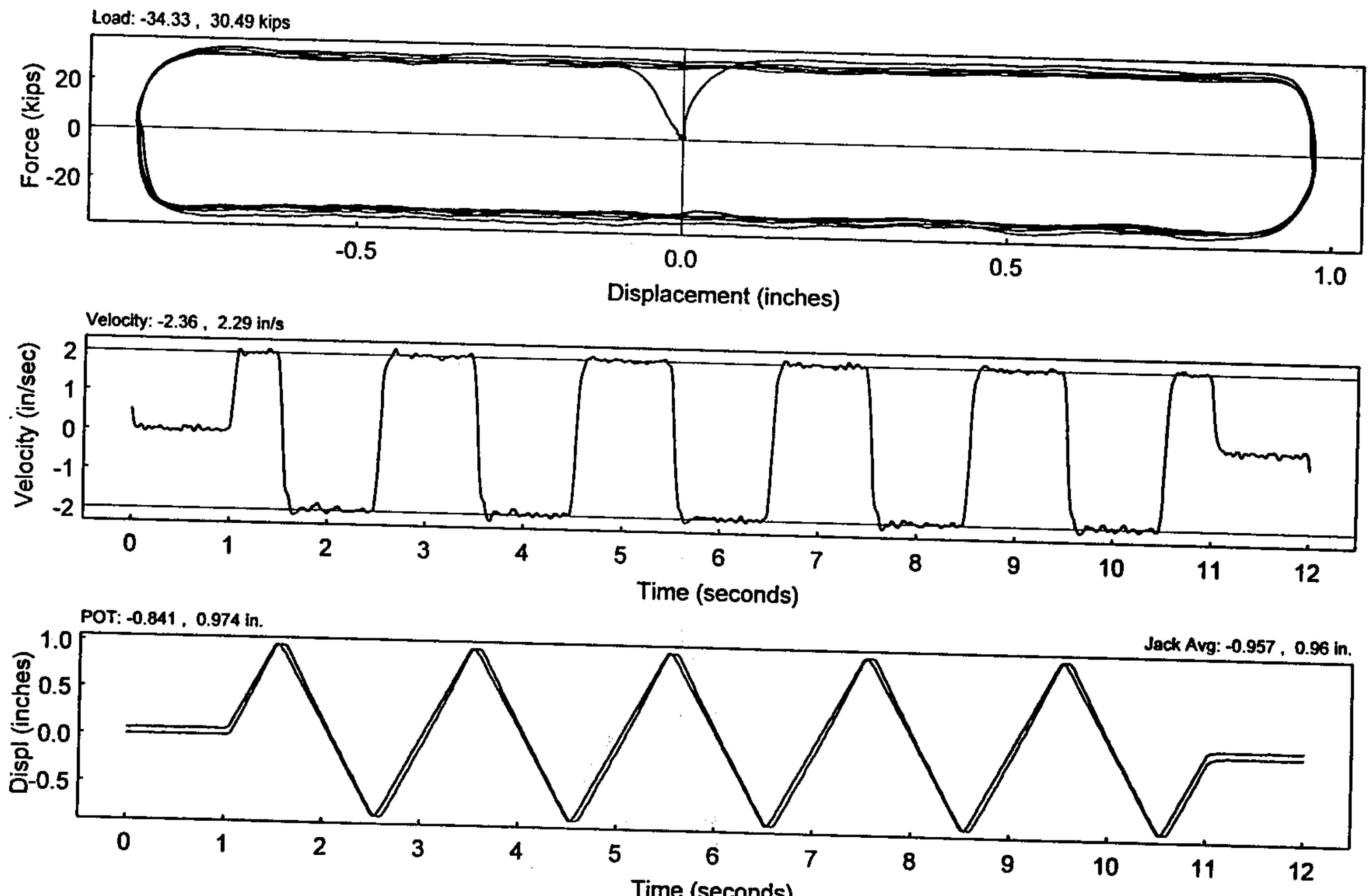
Damper: C

Test: sawc1
Target Velocity: 1 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 20:13:07 1995
Function: cvplot.s

File: 950512.05



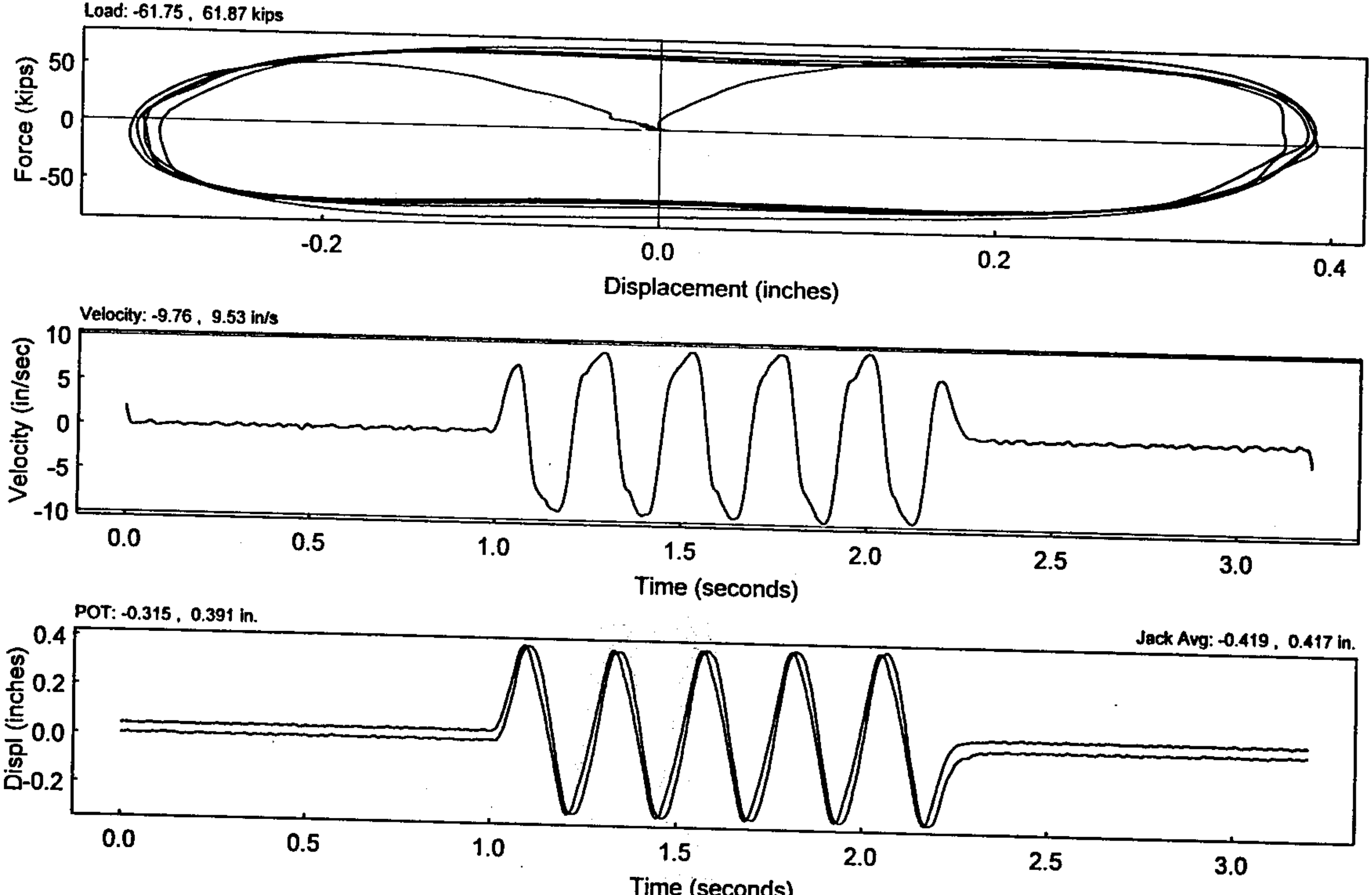
Damper: C

Test: sawc12
Target Velocity: 2 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 20:14:30 1995
Function: cvplot.s

File: 950512.06



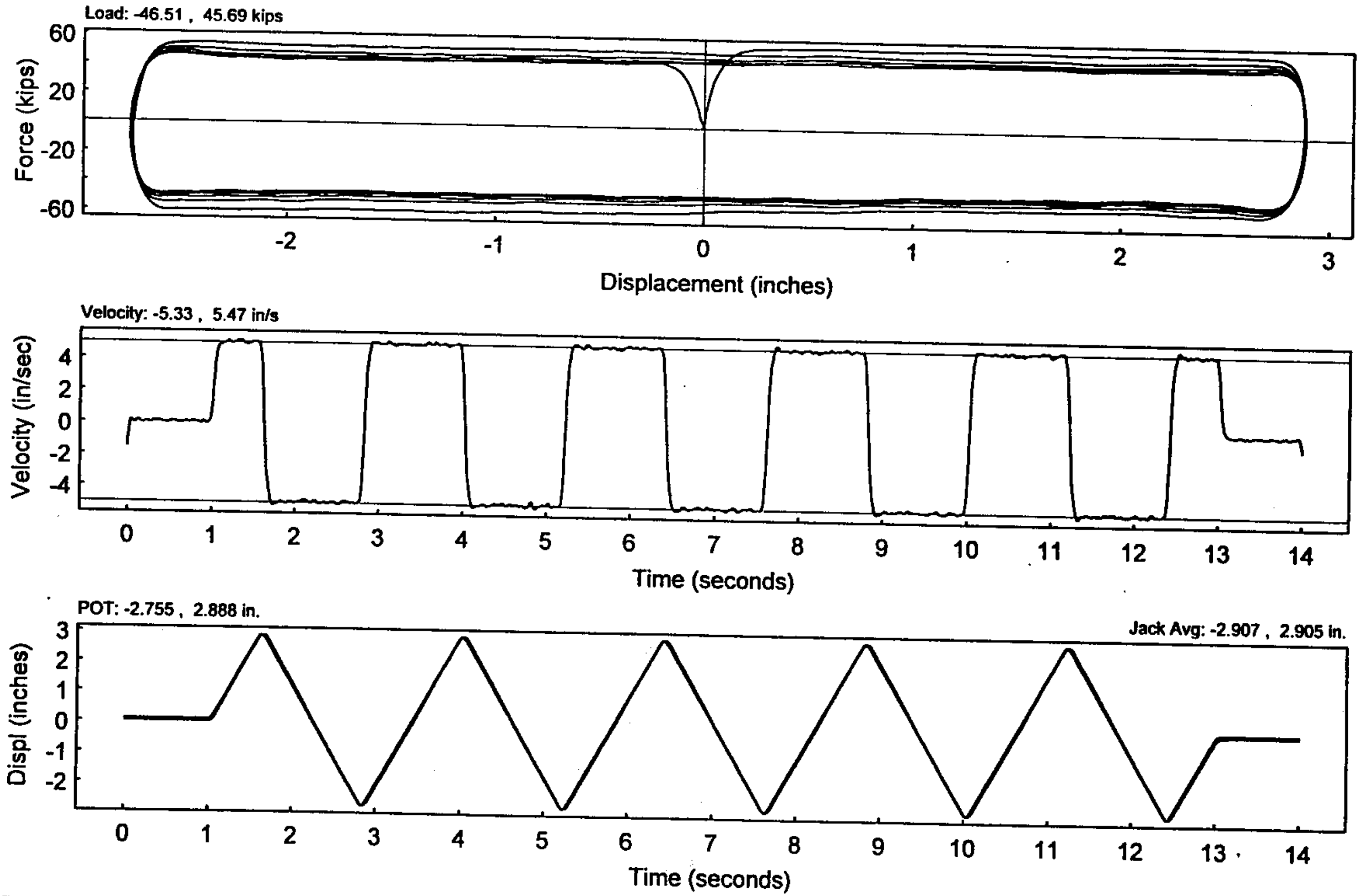
Damper: C

Test: sawc7
Target Velocity: 10 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Mon Dec 18 11:19:49 1995
Function: cvplot.s

File: 950512.07



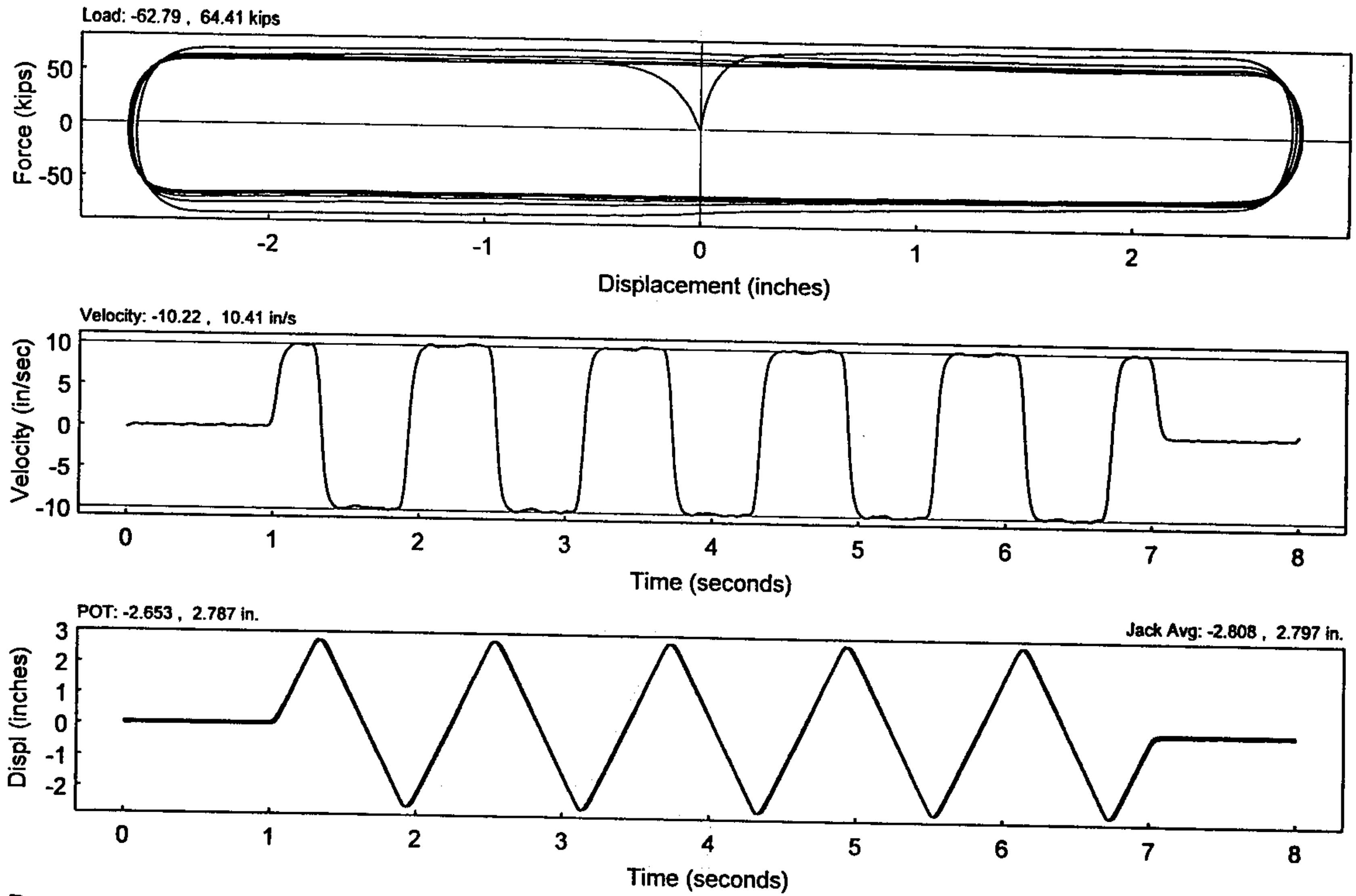
Damper: C

Test: sawc4
Target Velocity: 5 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 20:42:03 1995
Function: cvplot.s

File: 950512.08



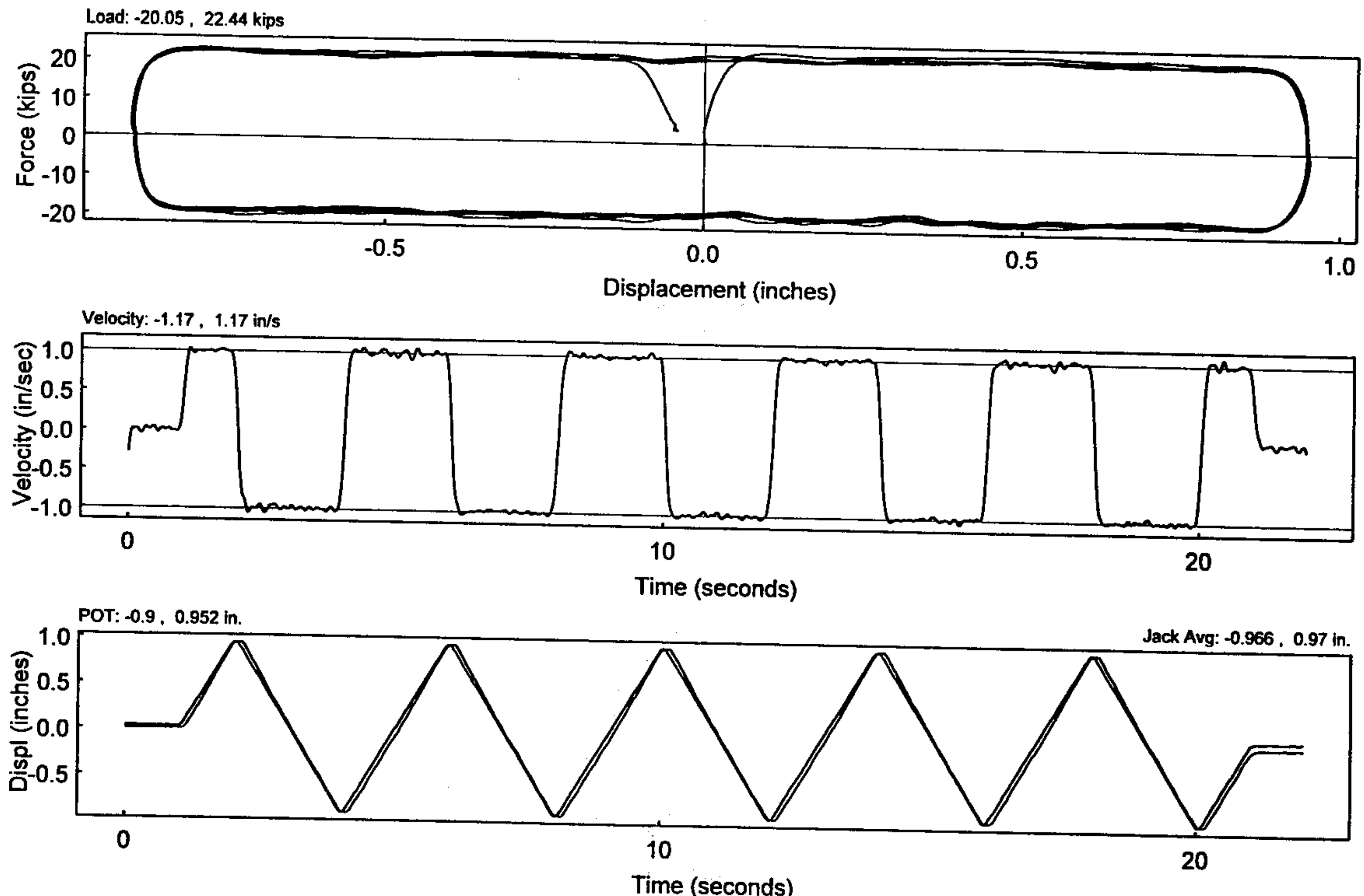
Damper: C

Test: sawc5
Target Velocity: 10 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 21:54:51 1995
Function: cvplot.s

File: 950512.09



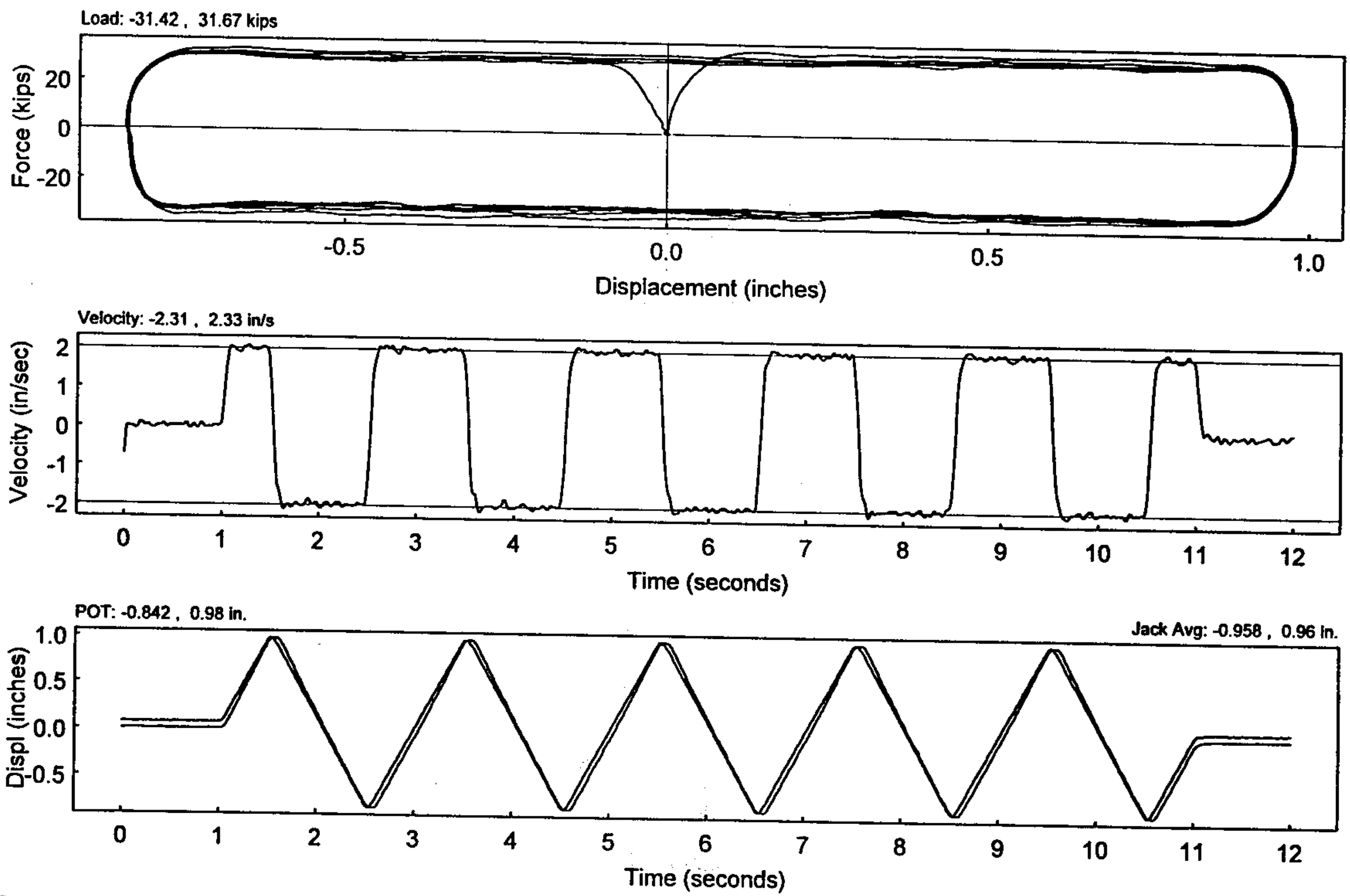
Damper: C

Test: sawc1
Target Velocity: 1 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 20:44:48 1995
Function: cvplot.s

File: 950512.12



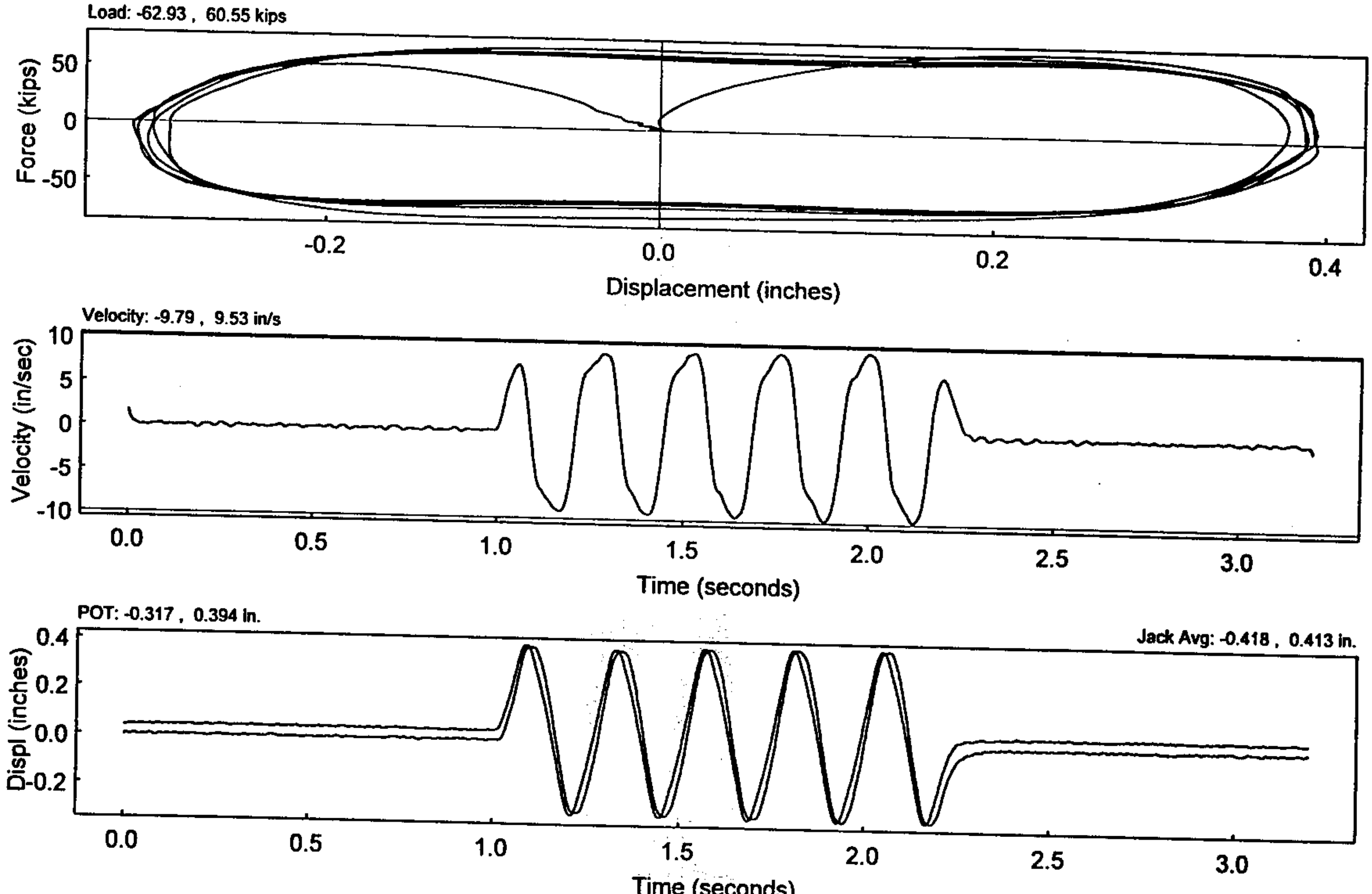
Damper: C

Test: sawc12
Target Velocity: 2 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 20:47:08 1995
Function: cvplot.s

File: 950512.13



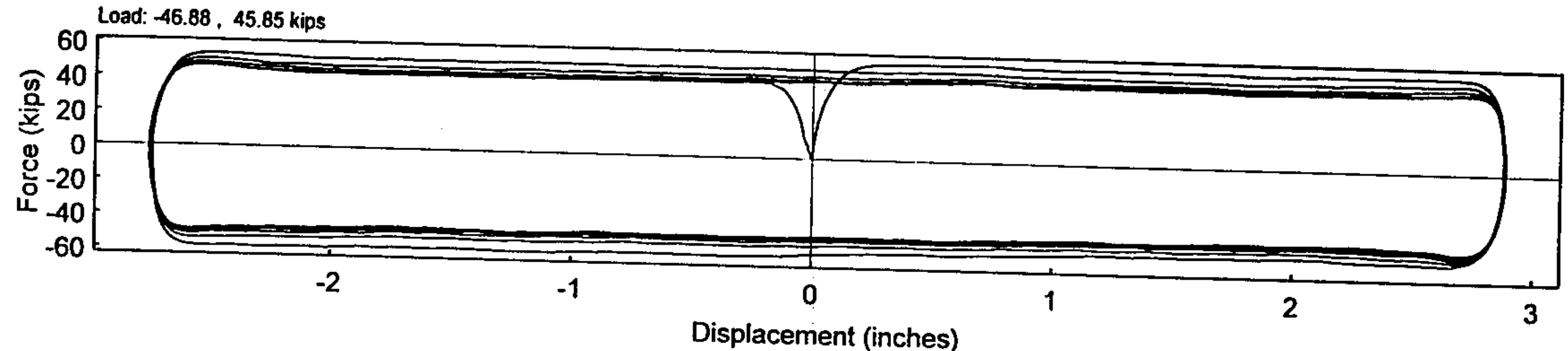
Damper: C

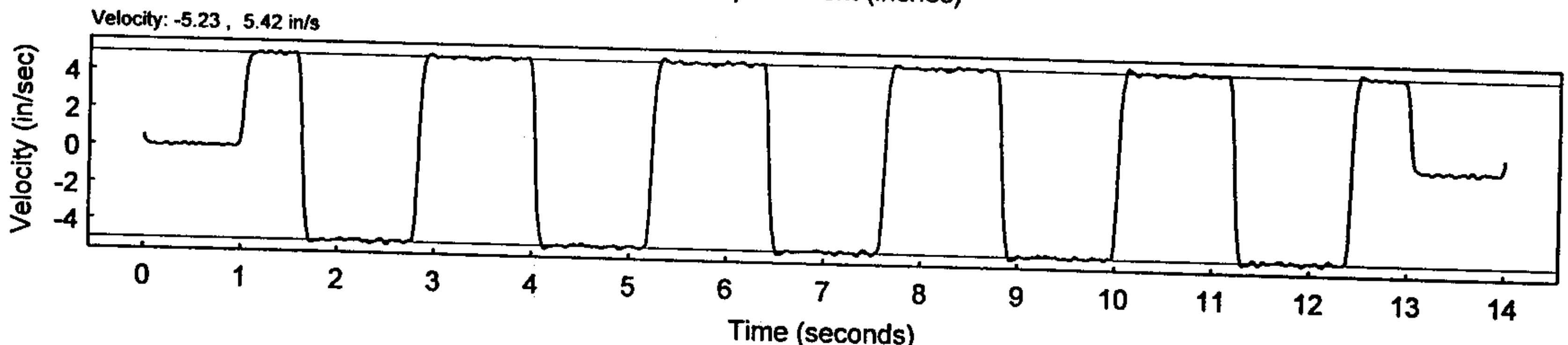
Test: sawc7
Target Velocity: 10 in/sec

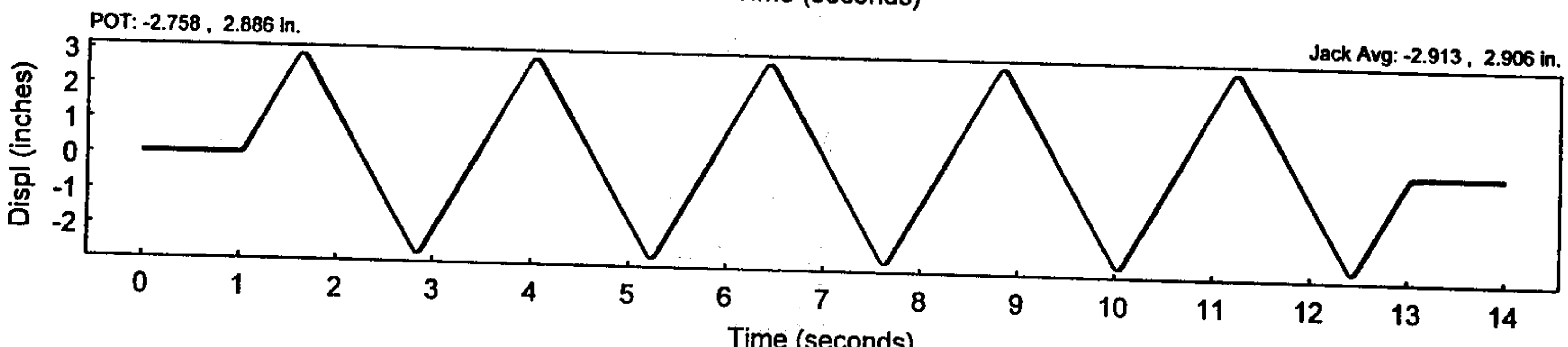
Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Mon Dec 18 11:21:54 1995
Function: cvplot.s

File: 950512.14







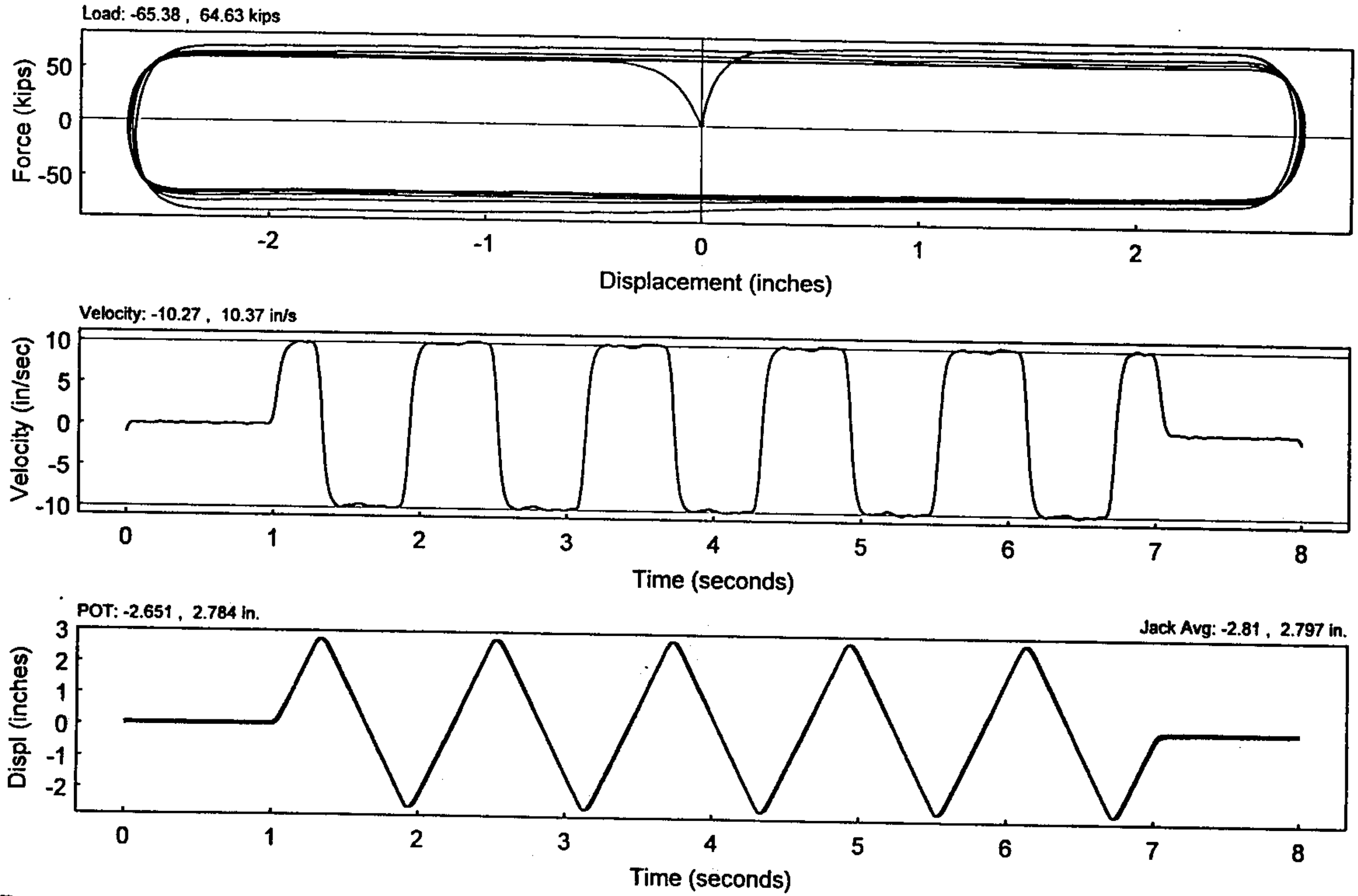
Damper: C

Test: sawc4
Target Velocity: 5 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 20:49:41 1995
Function: cvplot.s

File: 950512.15



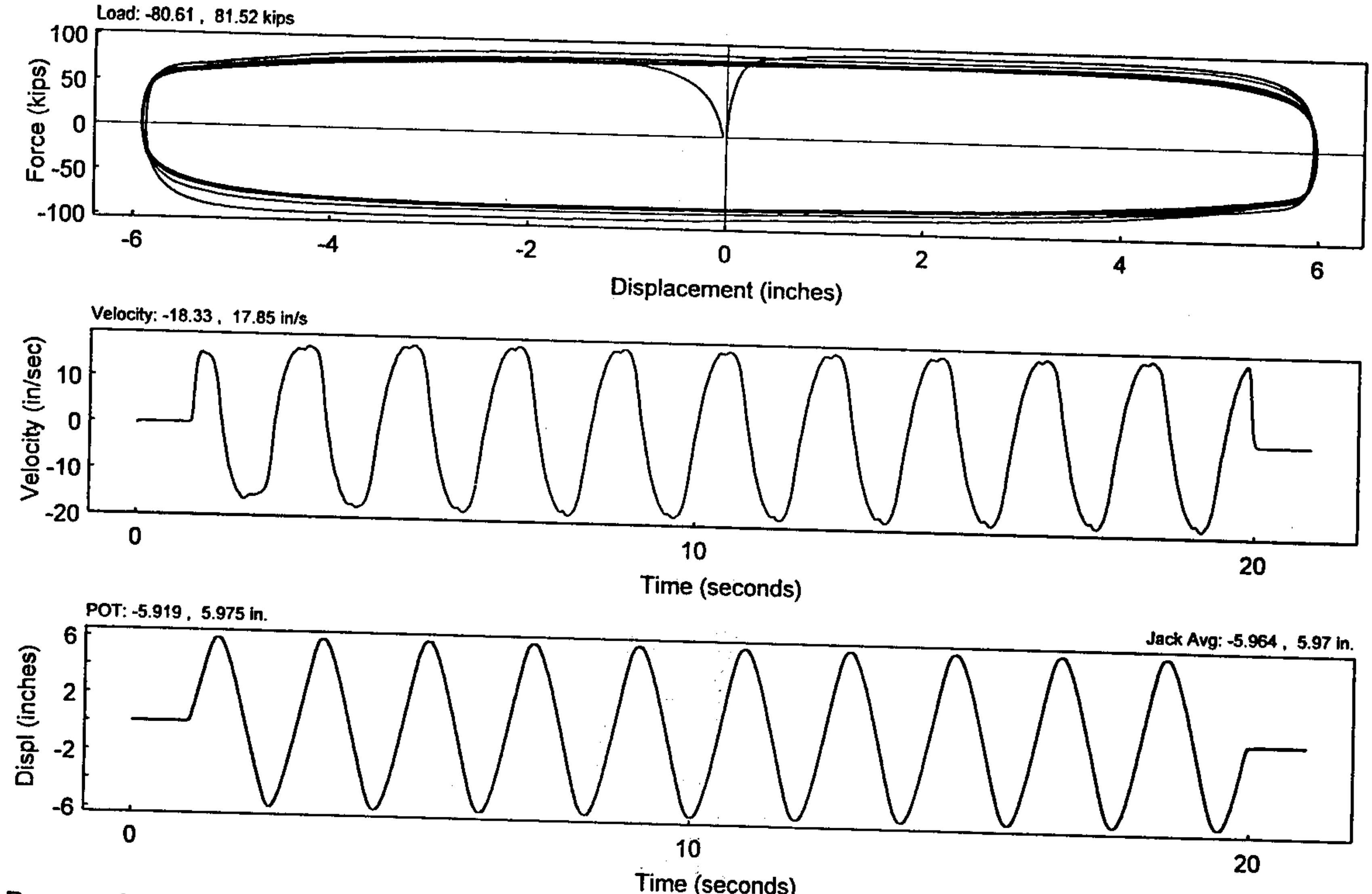
Damper: C

Test: sawc5
Target Velocity: 10 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 20:51:09 1995
Function: cvplot.s

File: 950512.16



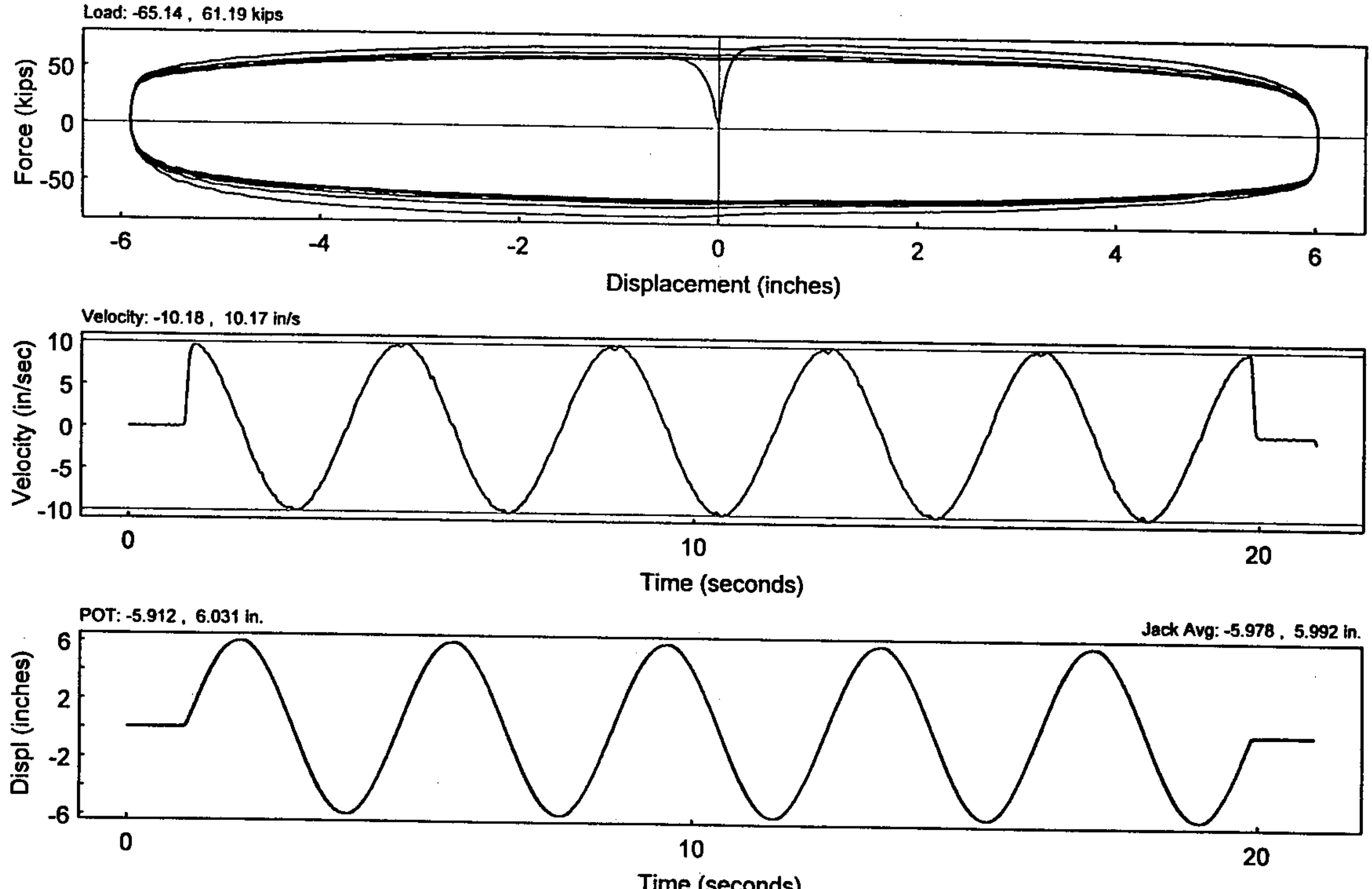
Damper: C

Test: sinc15
Target Velocity: 20 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 21:03:21 1995
Function: cvplot.s

File: 950512.21



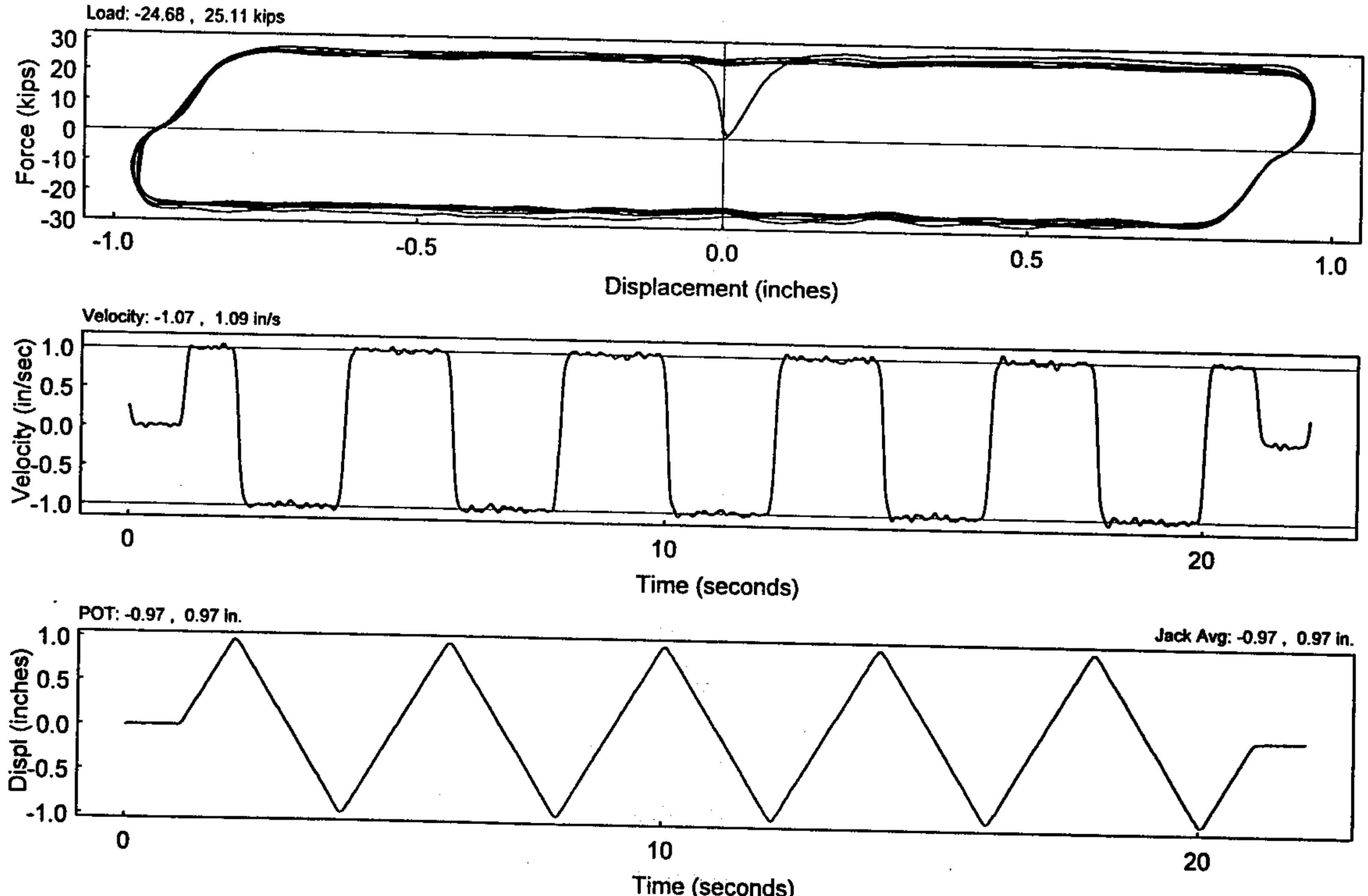
Damper: C

Test: sinc19
Target Velocity: 10 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 20:58:00 1995
Function: cvplot.s

File: 950512.20



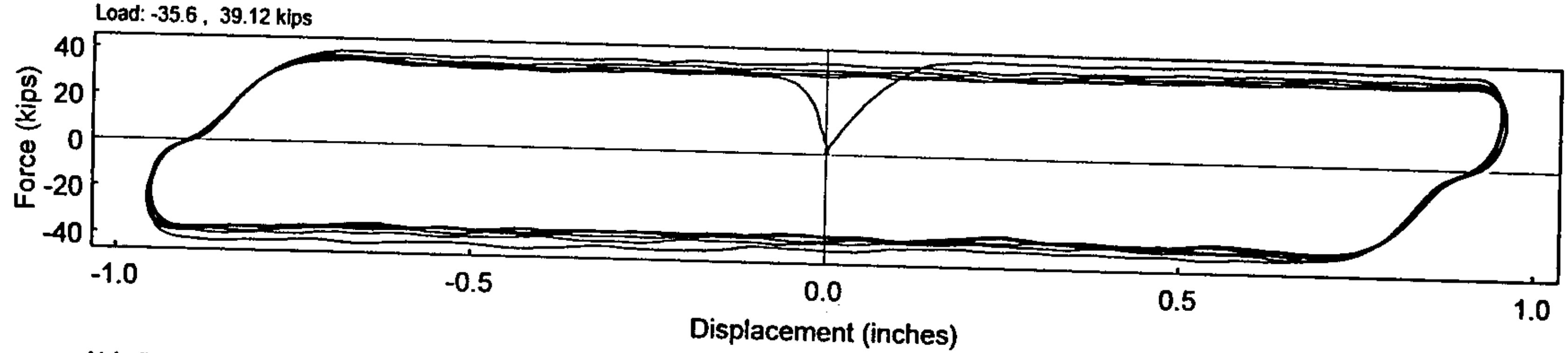
Damper: C

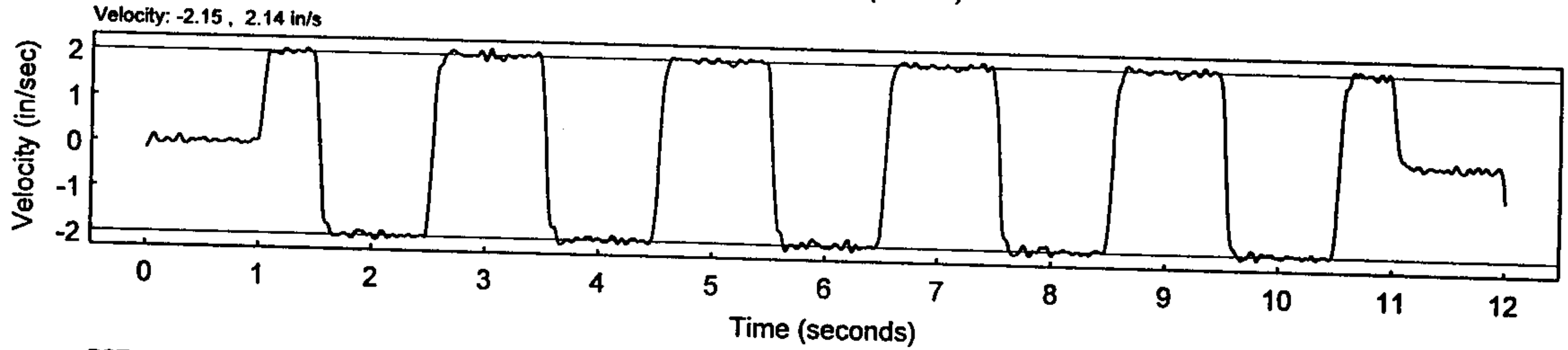
Test: sawc1
Target Velocity: 1 in/sec

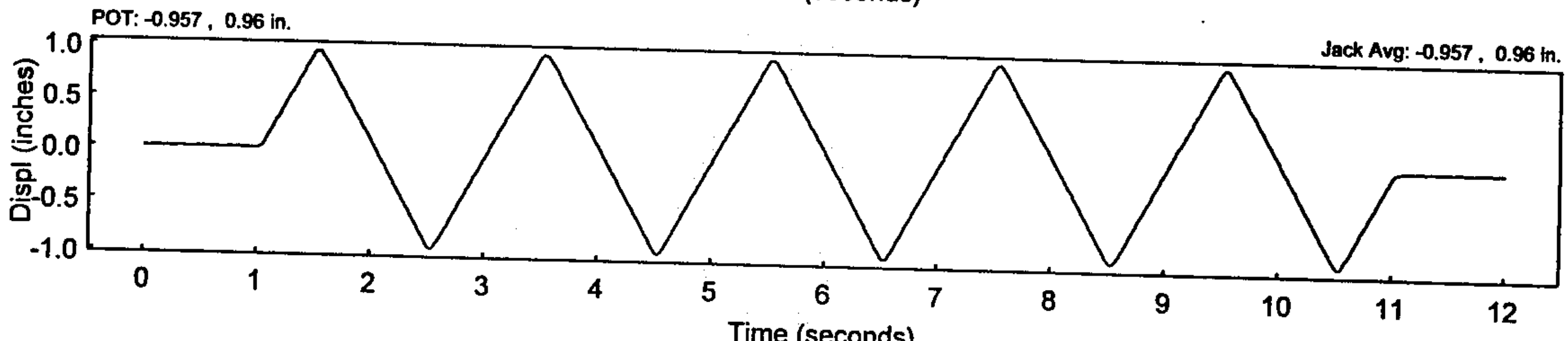
Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 21:05:30 1995
Function: cvplot.s

File: 950515.03







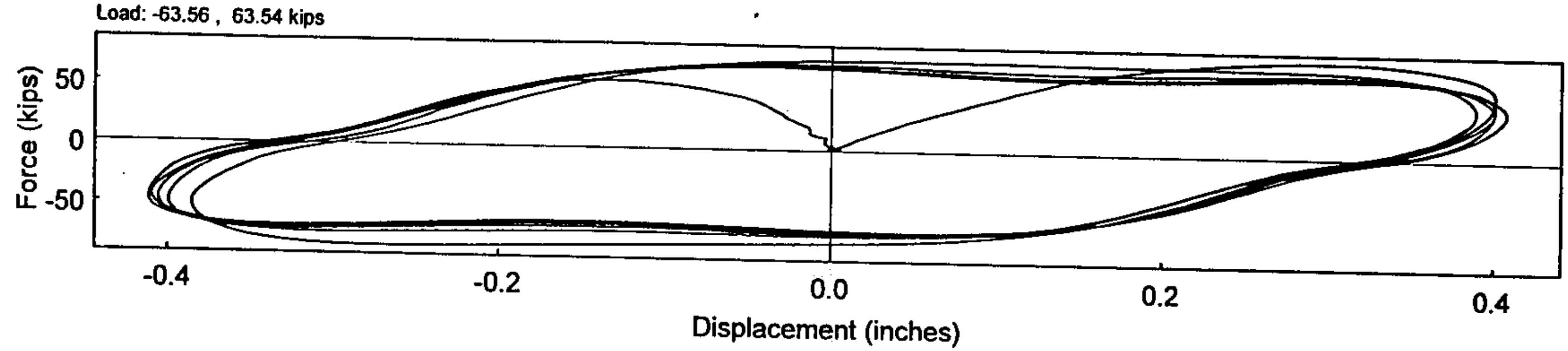
Damper: C

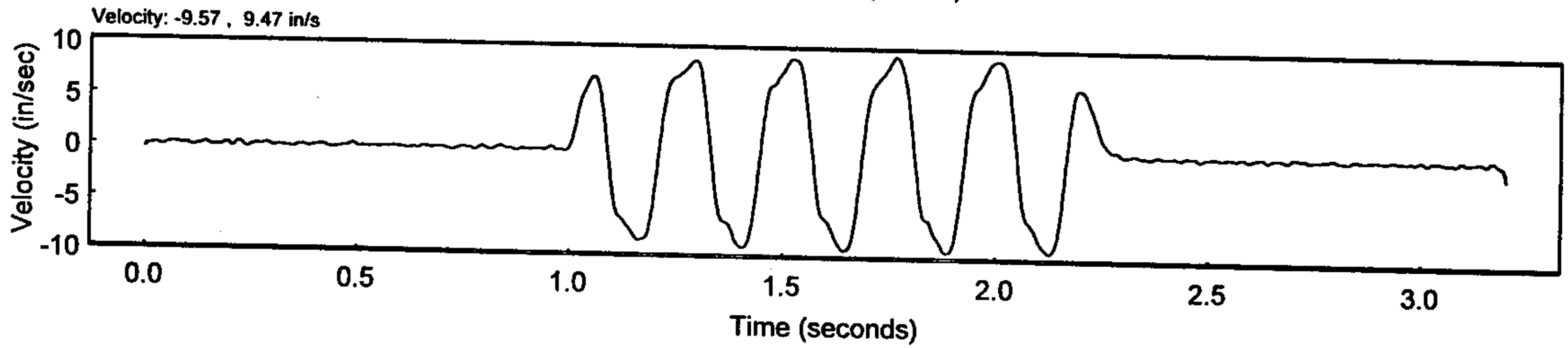
Test: sawc12
Target Velocity: 2 in/sec

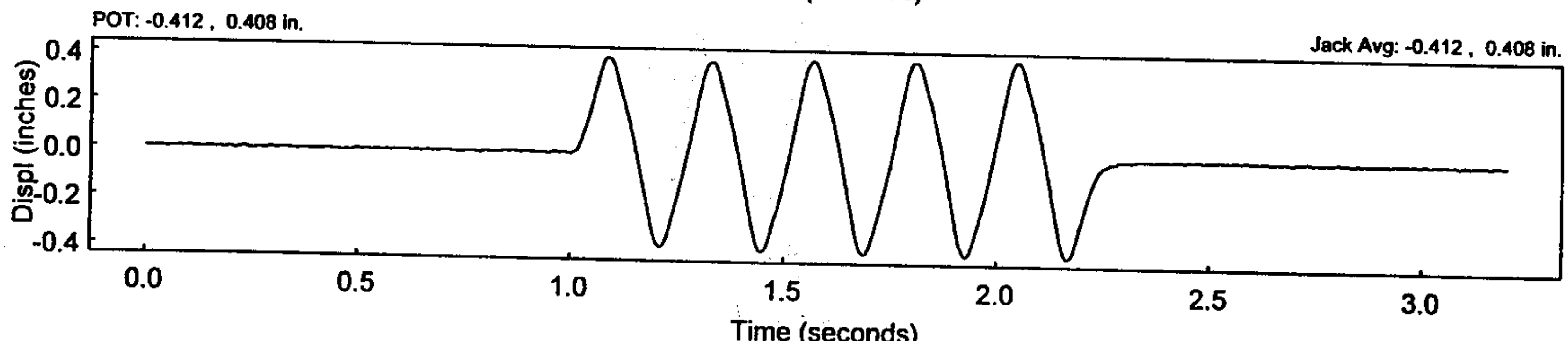
Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 21:08:54 1995
Function: cvplot.s

File: 950515.04







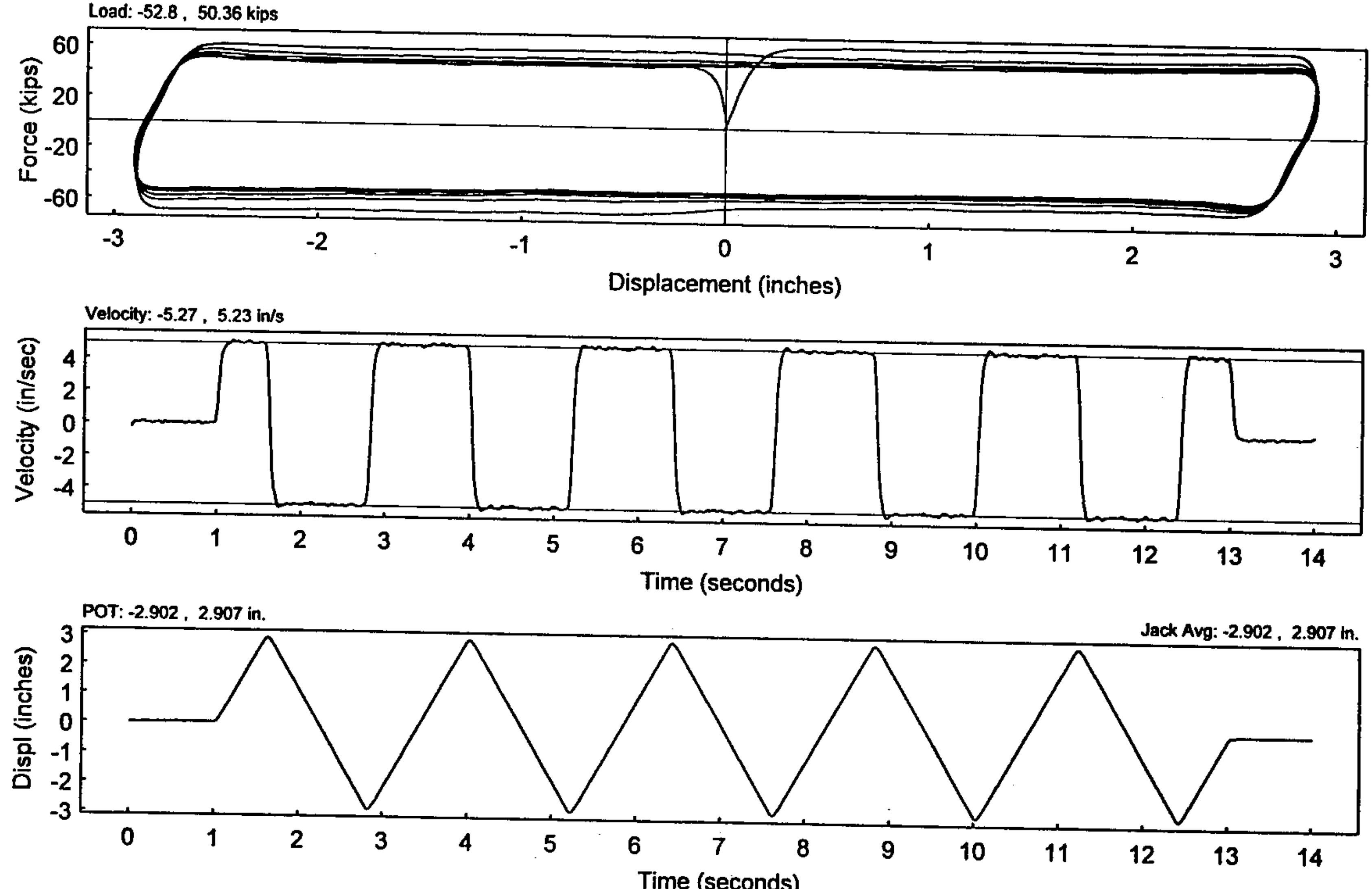
Damper: C

Test: sawc7
Target Velocity: 10 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Mon Dec 18 11:22:57 1995
Function: cvplot.s

File: 950515.05



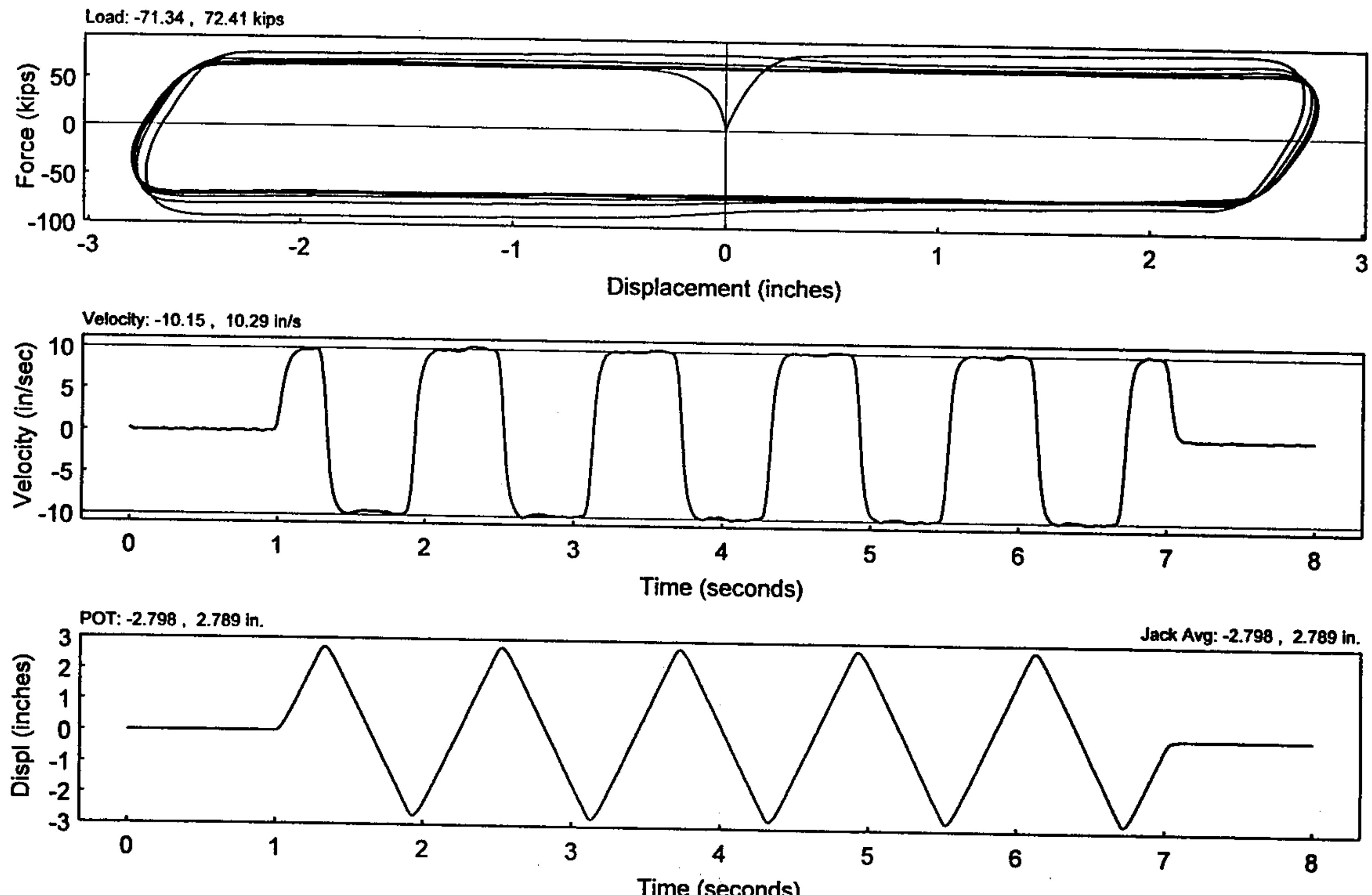
Damper: C

Test: sawc4
Target Velocity: 5 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 21:11:01 1995
Function: cvplot.s

File: 950515.06



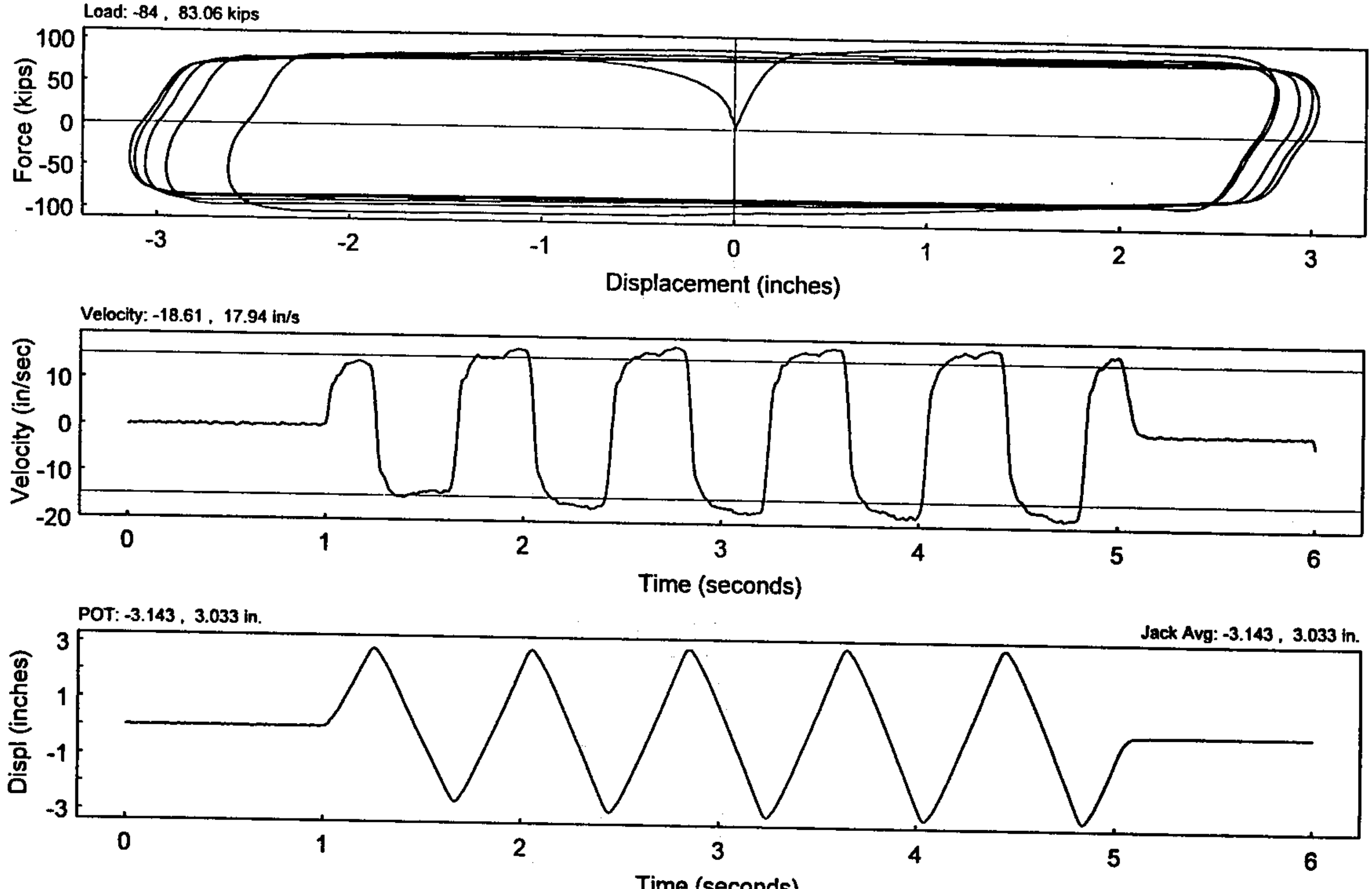
Damper: C

Test: sawc5
Target Velocity: 10 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 21:11:55 1995
Function: cvplot.s

File: 950515.07



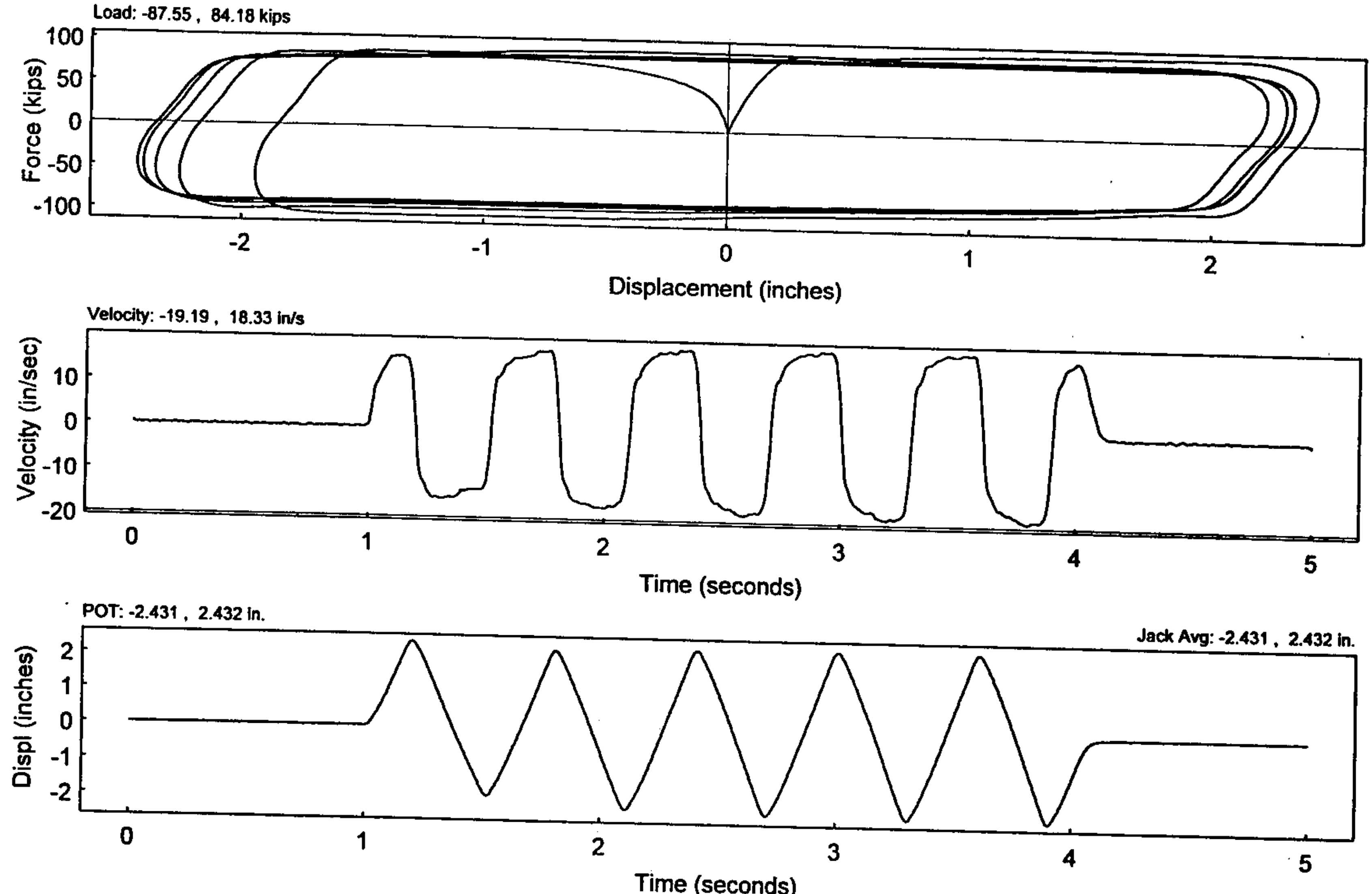
Damper: C

Test: sawc14
Target Velocity: 15 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 21:13:26 1995
Function: cvplot.s

File: 950515.08



Damper: C

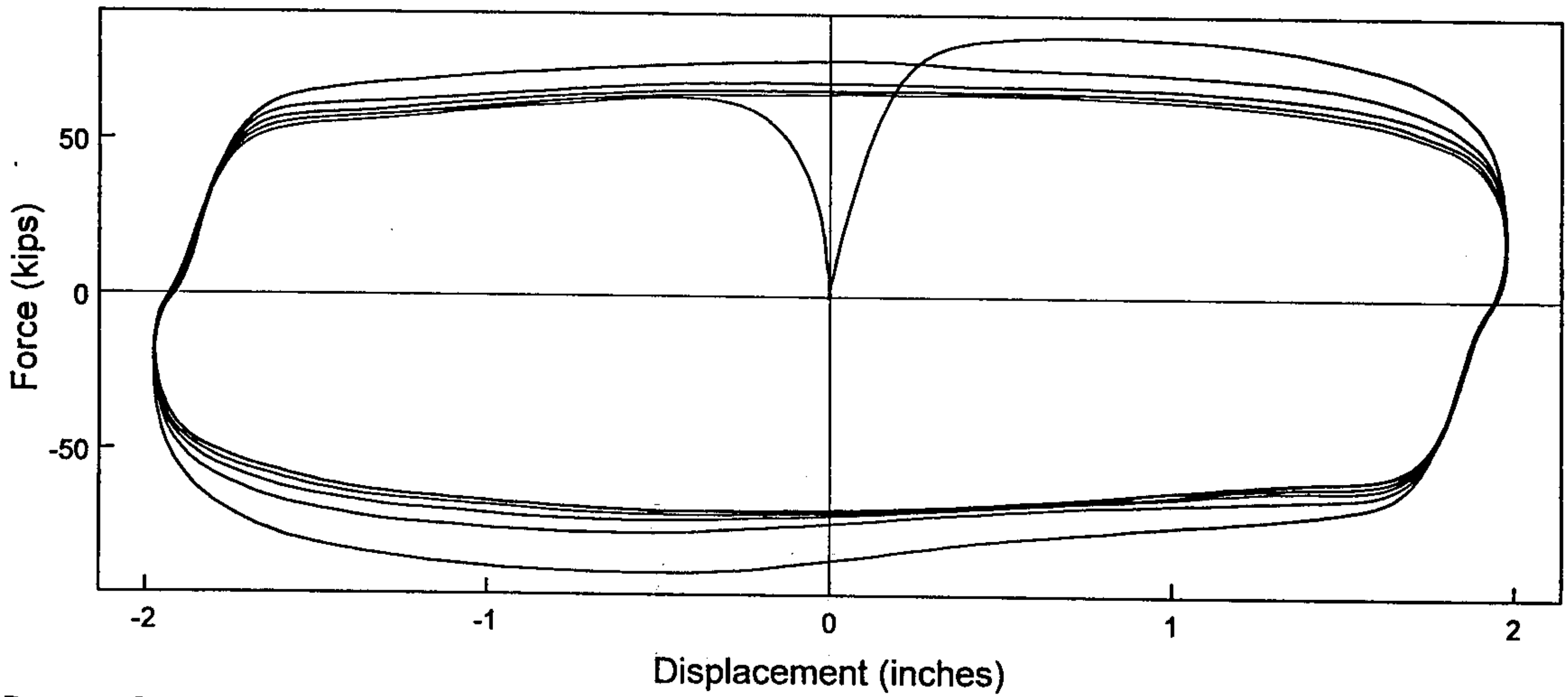
Test: sawc9
Target Velocity: 20 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 21:14:37 1995
Function: cvplot.s

File: 950515.09

	Loop 2	Loop 3	Loop 4
Fmax, Fmin [kips]	75.7 , -76.03	68.51 , -72.11	66.13 , -70.32
Dmax, Dmin [in.]	1.98 , -1.98	1.98 , -1.98	1.98 , -1.98
Aloop, Abox [k-in.]	513.7 , 599.8	487.2 , 555.8	477.6 , 539.6
Efficiency [%]	85.7	87.7	88.5



Damper: C

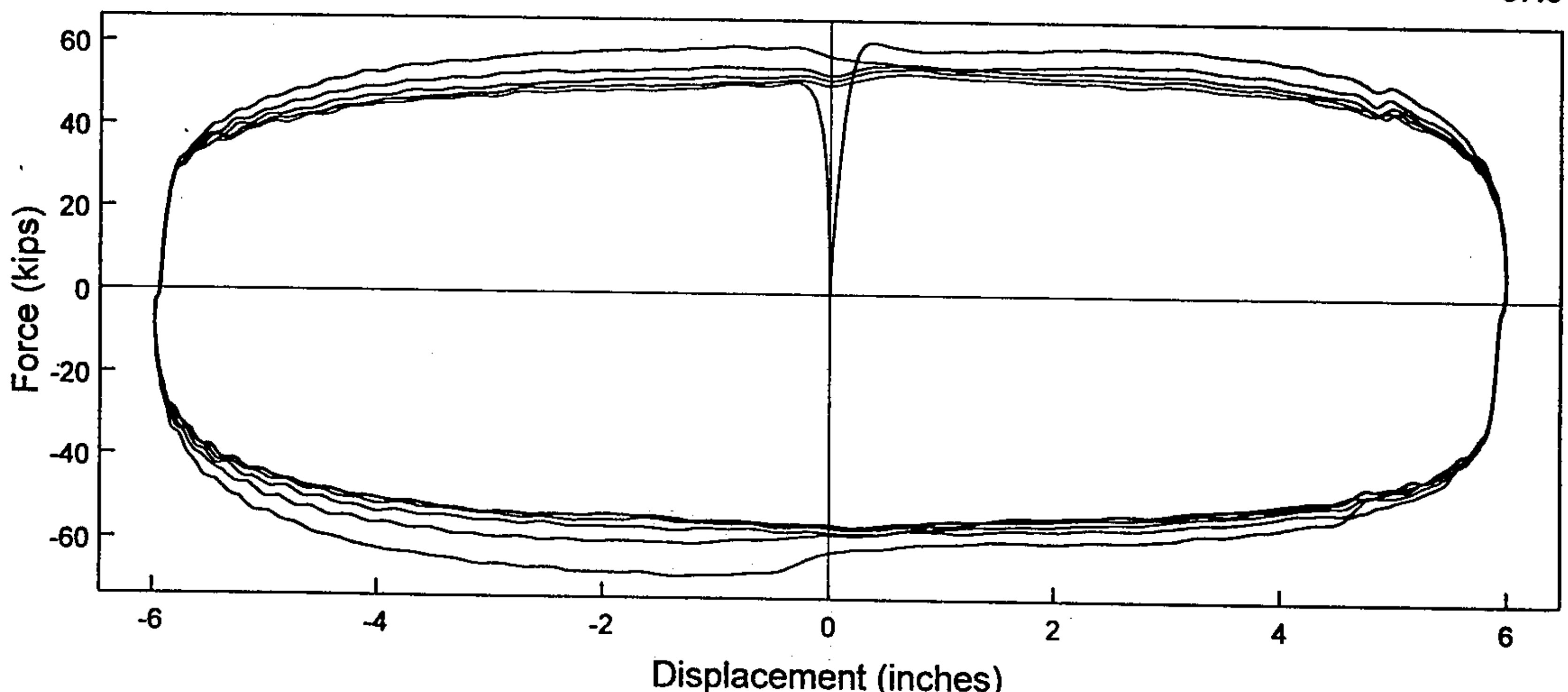
Test: sinc16

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Fri Oct 27 22:39:46 1995
Function: edplot.s

File: 950515.10

	Loop 2	Loop 3	Loop 4
Fmax, Fmin [kips]	57.38 , -60.67	55.54 , -58.07	54.54 , -57.11
Dmax, Dmin [in.]	5.99 , -5.99	5.99 , -5.99	5.99 , -5.99
Aloop, Abox [k-in.]	1243.3 , 1413.9	1199.3 , 1360.4	1174.1 , 1336.8
Efficiency [%]	87.9	88.2	87.8



Damper: C

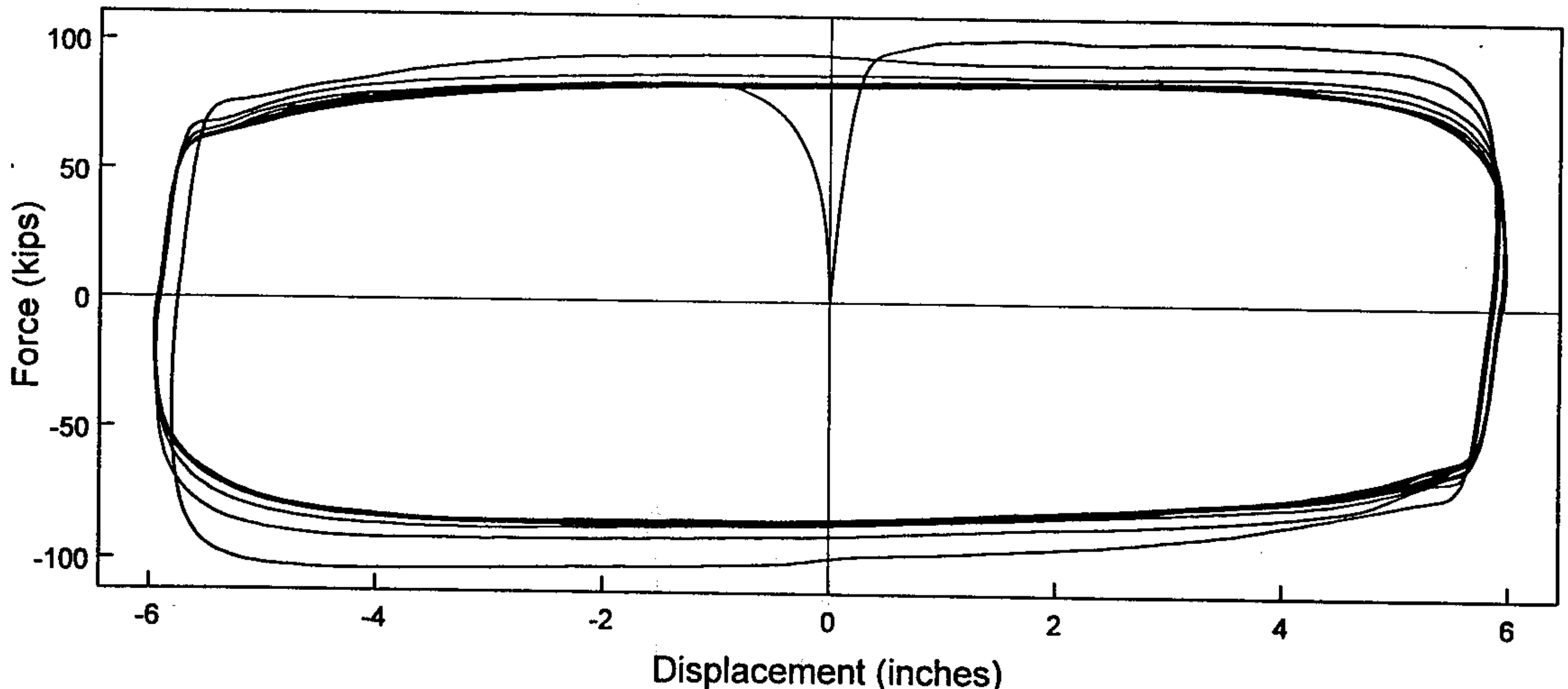
Test: sinc17

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Fri Oct 27 22:40:26 1995
Function: edplot.s

File: 950515.11

	Loop 2	Loop 3	Loop 4
Fmax, Fmin [kips]	95.33 , -91.81	87.95 , -87.62	86.12 , -85.97
Dmax, Dmin [in.]	5.9 , -5.95	5.95 , -5.96	5.96 , -5.96
Aloop, Abox [k-in.]	2027.2 , 2217.4	1929.4 , 2090.8	1890 , 2051
Efficiency [%]	91.4	92.3	92.1



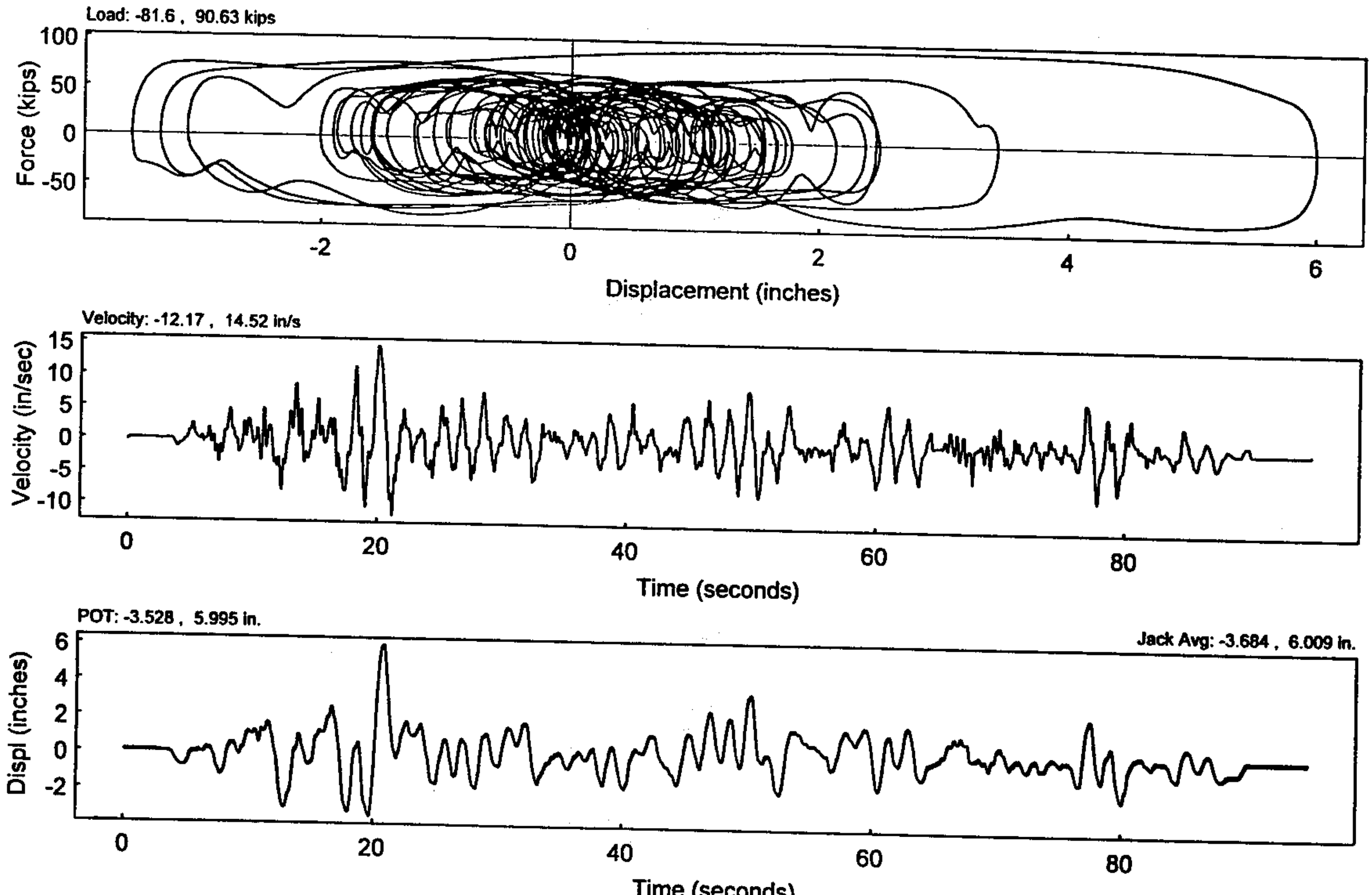
Damper: C

Test: sinc15

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Fri Oct 27 22:41:14 1995
Function: edplot.s

File: 950515.12



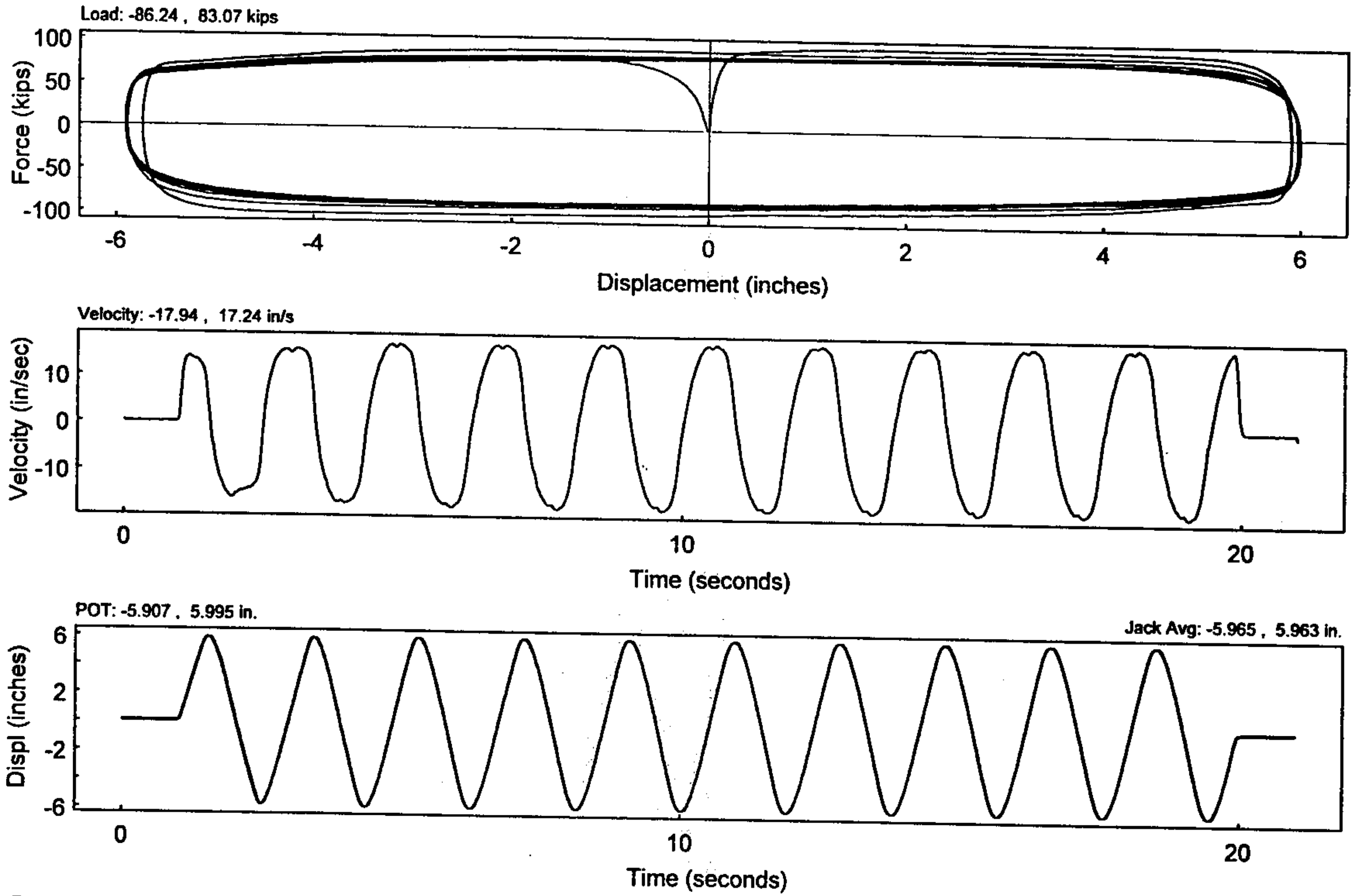
Damper: C

Test: eqd0.5
Target Velocity: 20 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 21:18:59 1995
Function: cvplot.s

File: 950516.01



Damper: C

Test: sinc15
Target Velocity: 20 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

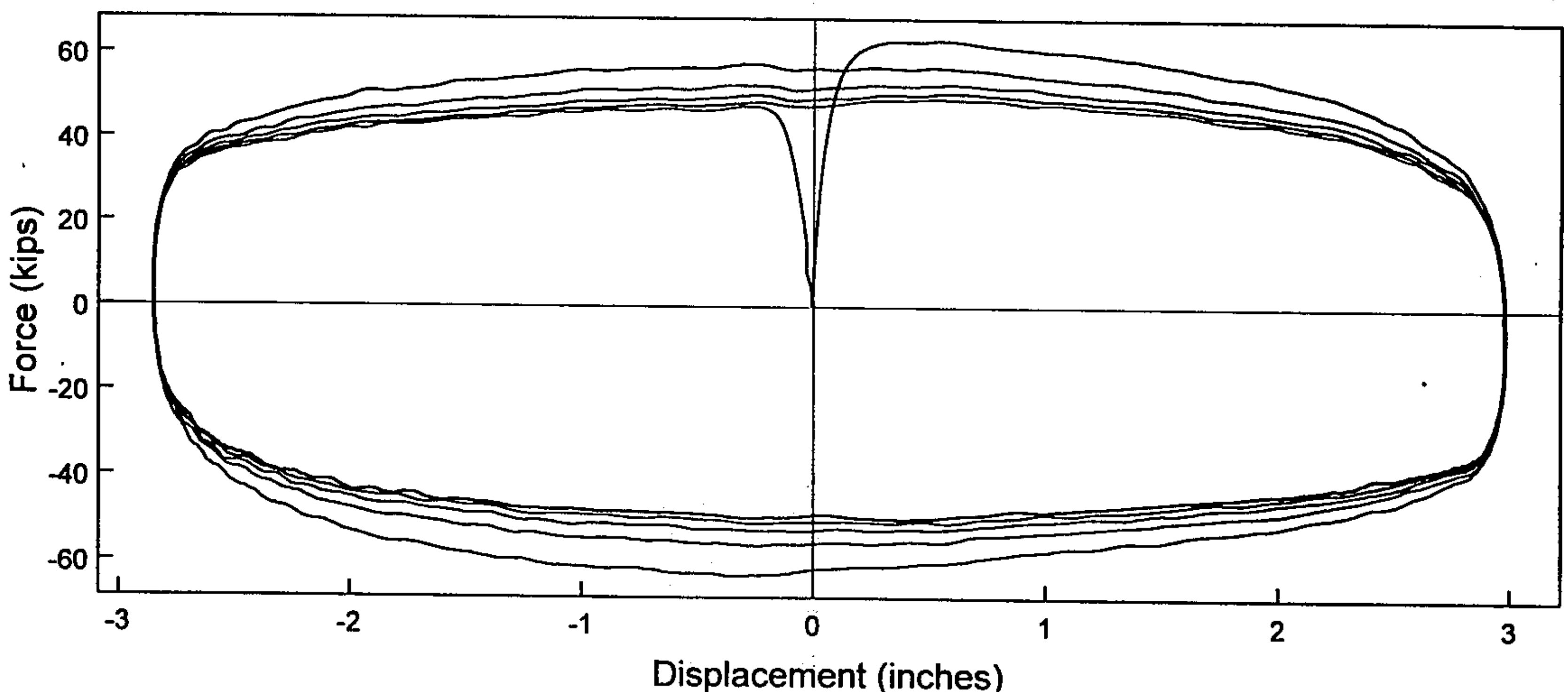
Plotted:Sun Jun 11 21:20:24 1995
Function: cvplot.s

File: 950516.02

Appendix B

Results for Sinusoidal Energy-Dissipation Tests

	Loop 2	Loop 3	Loop 4
Fmax, Fmin [kips]	56.89 , -56.22	52.74 , -52.96	50.72 , -51.15
Dmax, Dmin [in.]	2.98 , -2.85	2.98 , -2.85	2.98 , -2.85
Aloop, Abox [k-in.]	564.3 , 660	535.8 , 616.5	518.4 , 593.9
Efficiency [%]	85.5	86.9	87.3



Damper: C

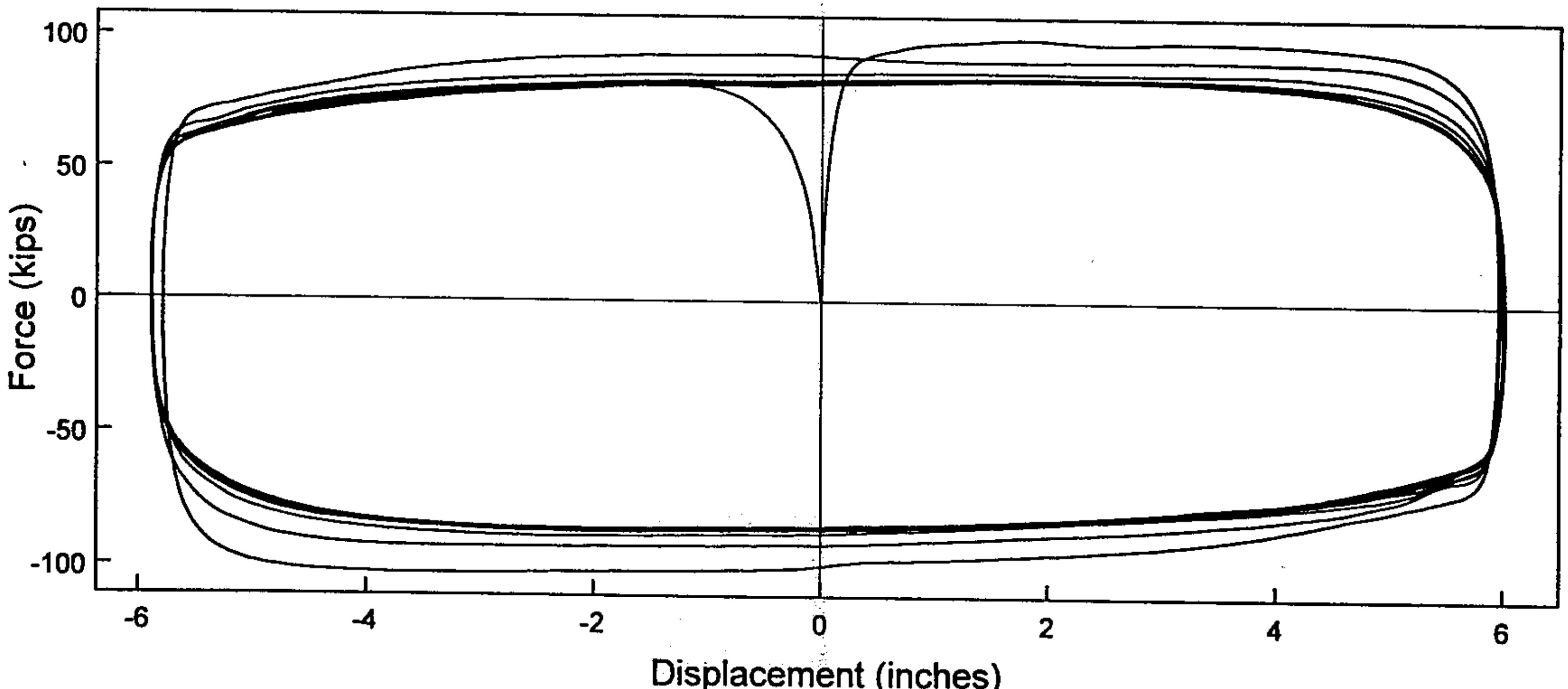
Test: sinc10

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Fri Oct 27 22:17:07 1995
Function: edplot.s

File: 950511.11

	Loop 2	Loop 3	Loop 4
Fmax, Fmin [kips]	92.72 , -92.68	86.51 , -88.64	84.65 , -87.15
Dmax, Dmin [in.]	5.97 , -5.89	6 , -5.89	6 , -5.89
Aloop, Abox [k-in.]	2011.2 , 2197.5	1915.8 , 2081.7	1874.5 , 2043.3
Efficiency [%]	91.5	92	91.7



Damper: C

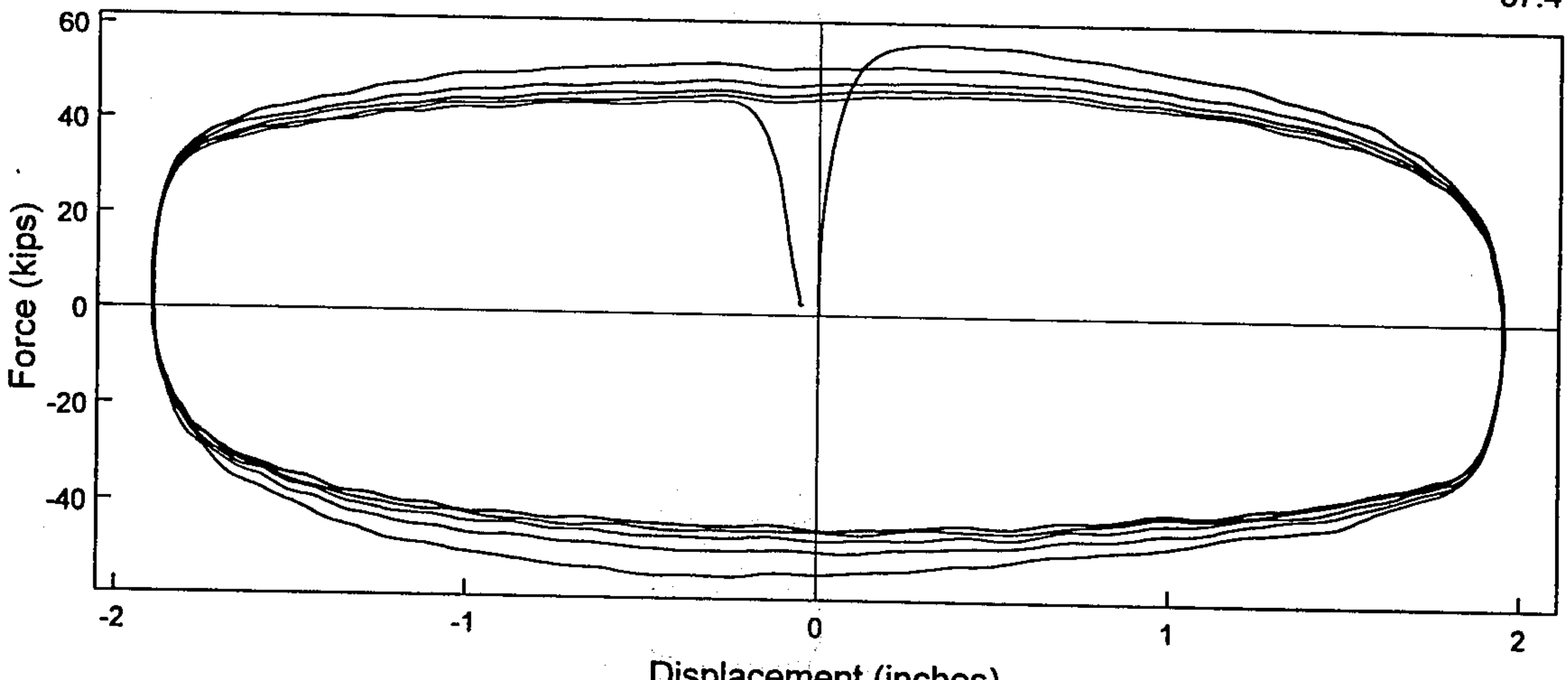
Test: sinc15

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Fri Oct 27 22:36:17 1995
Function: edplot.s

File: 950511.16

	Loop 2	Loop 3	Loop 4
Fmax, Fmin [kips]	52.33 , -49.49	49.04 , -47.02	47.41 , -45.68
Dmax, Dmin [in.]	1.95 , -1.9	1.95 , -1.9	1.95 , -1.9
Aloop, Abox [k-in.]	335.7 , 391.5	322.4 , 369.7	312.8 , 358.1
Efficiency [%]	85.7	87.2	87.4



Damper: C

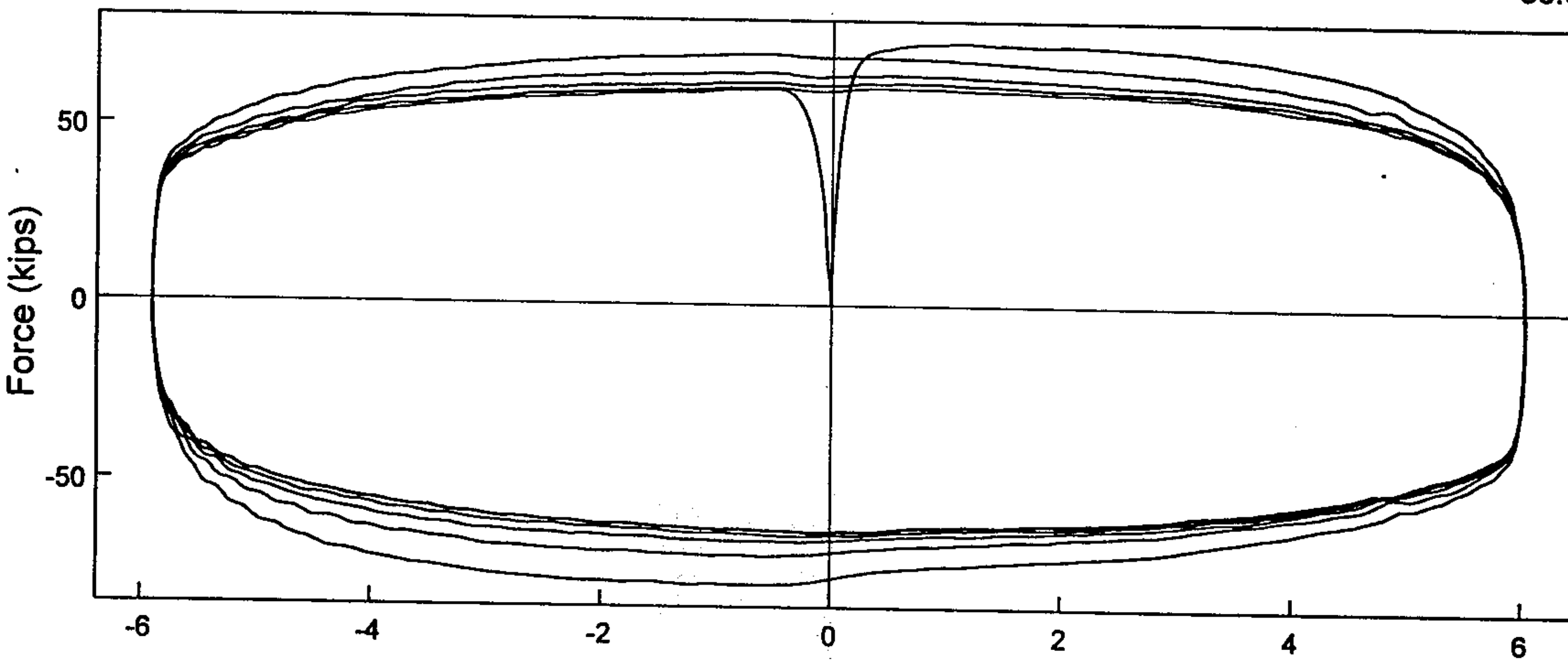
Test: sinc18

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Fri Oct 27 22:37:27 1995
Function: edplot.s

File: 950512.19

	Loop 2	Loop 3	Loop 4
Fmax, Fmin [kips]	69.87 , -70.36	65.05 , -66.42	62.82 , -64.87
Dmax, Dmin [in.]	6.03 , -5.91	6.03 , -5.91	6.03 , -5.91
Aloop, Abox [k-in.]	1453.1 , 1673.7	1383.3 , 1570	1348.9 , 1524.3
Efficiency [%]	86.8	88.1	88.5



Damper: C

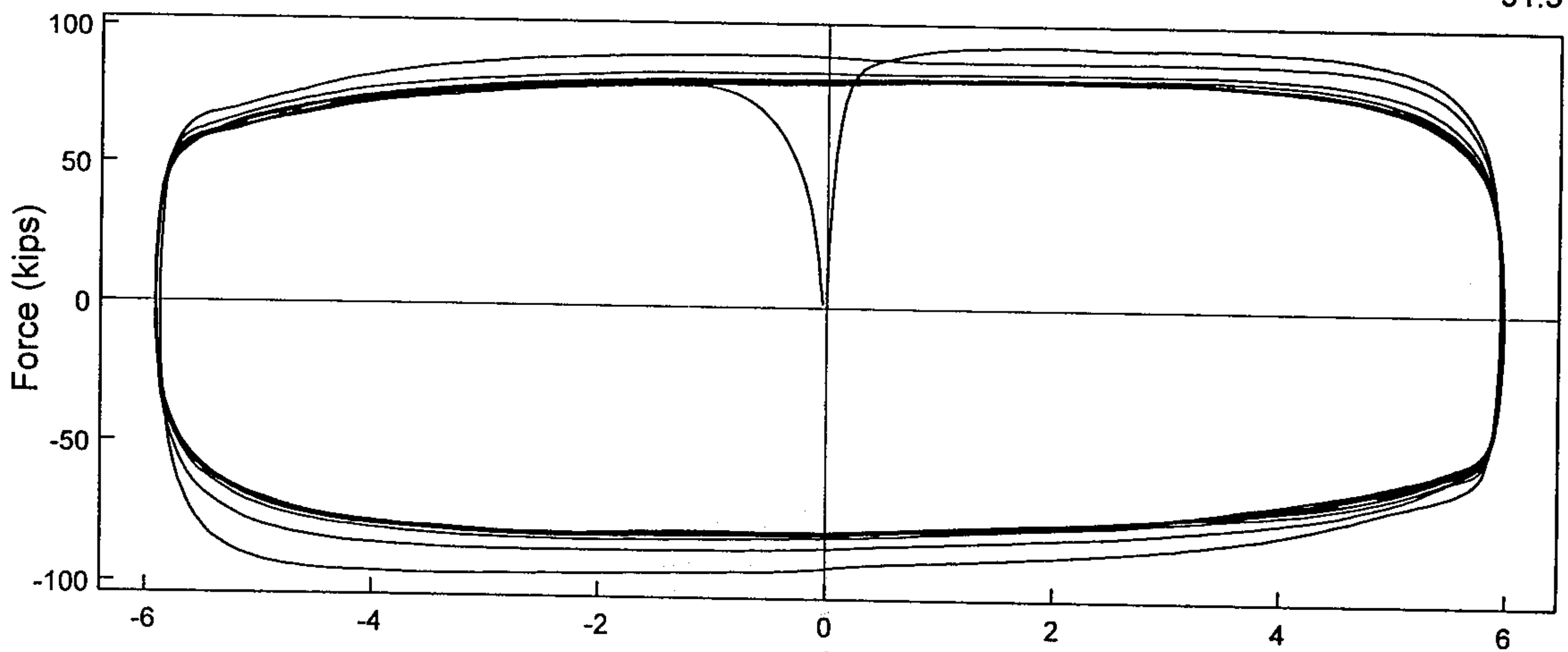
Test: sinc19

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Fri Oct 27 22:38:20 1995
Function: edplot.s

File: 950512.20

	Loop 2	Loop 3	Loop 4
Fmax, Fmin [kips]	90.67 , -87.58	84.84 , -83.83	83.09 , -82.19
Dmax, Dmin [in.]	5.95 , -5.91	5.96 , -5.92	5.97 , -5.91
Aloop, Abox [k-in.]	1916.8 , 2113.9	1831.5 , 2003.6	1792.7 , 1964.1
Efficiency [%]	90.7	91.4	91.3



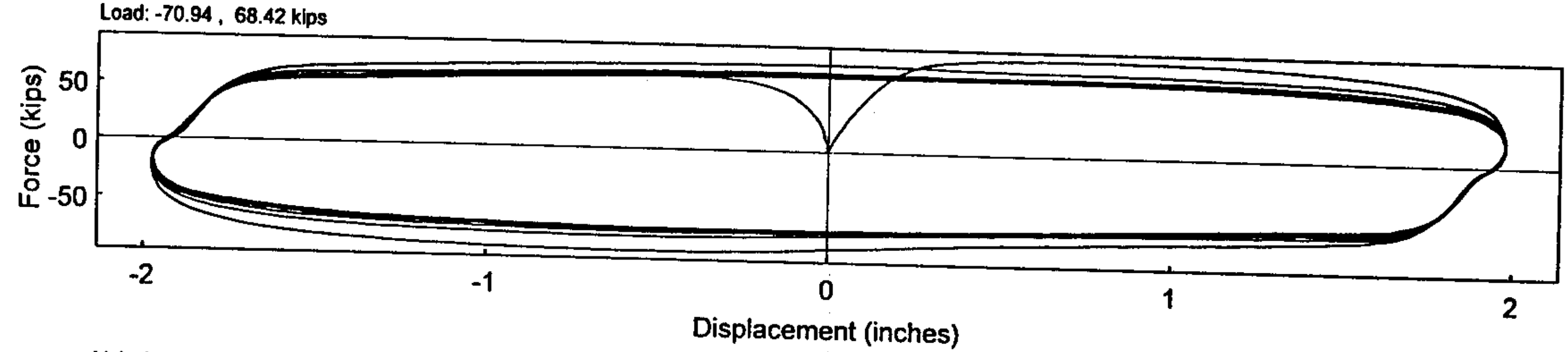
Damper: C

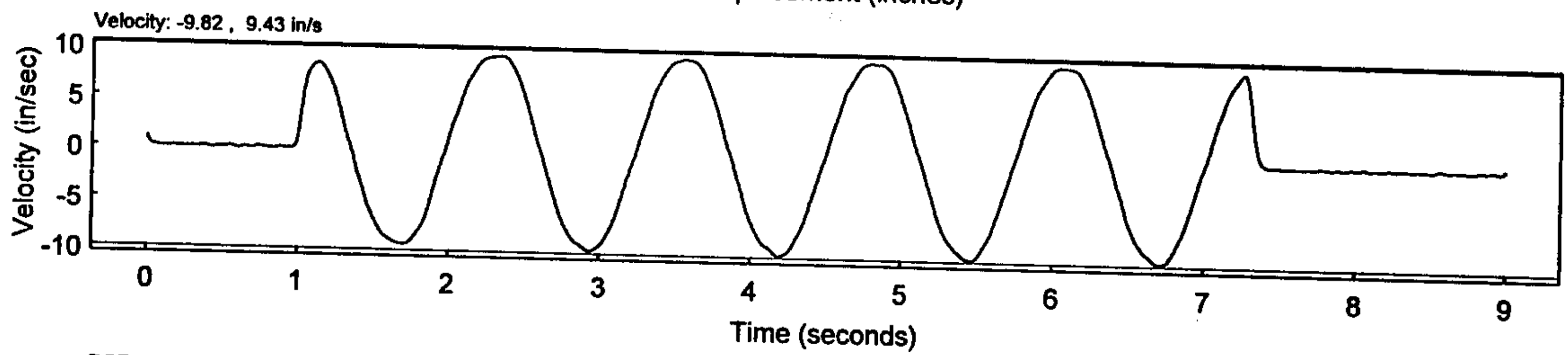
Test: sinc15

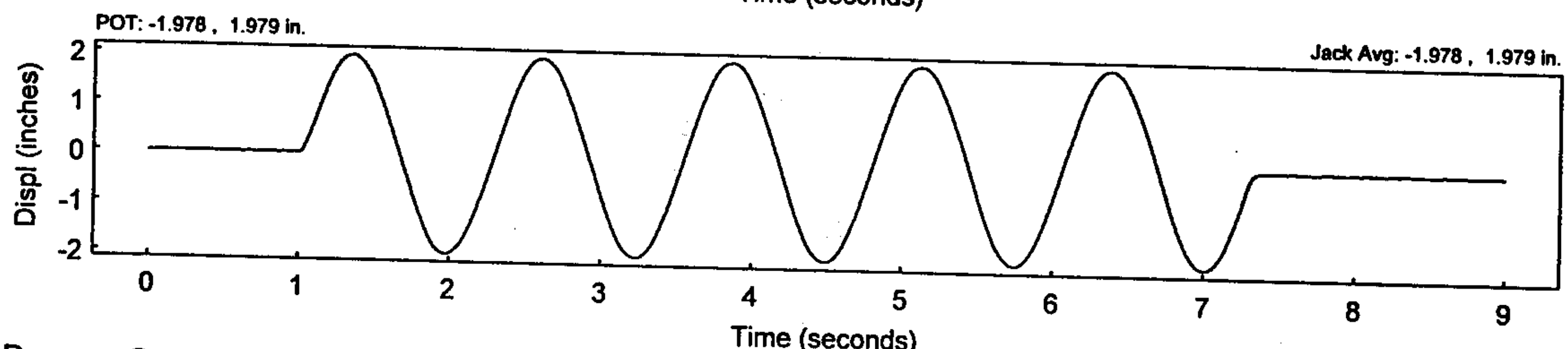
Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Fri Oct 27 22:38:57 1995
Function: edplot.s

File: 950512.21







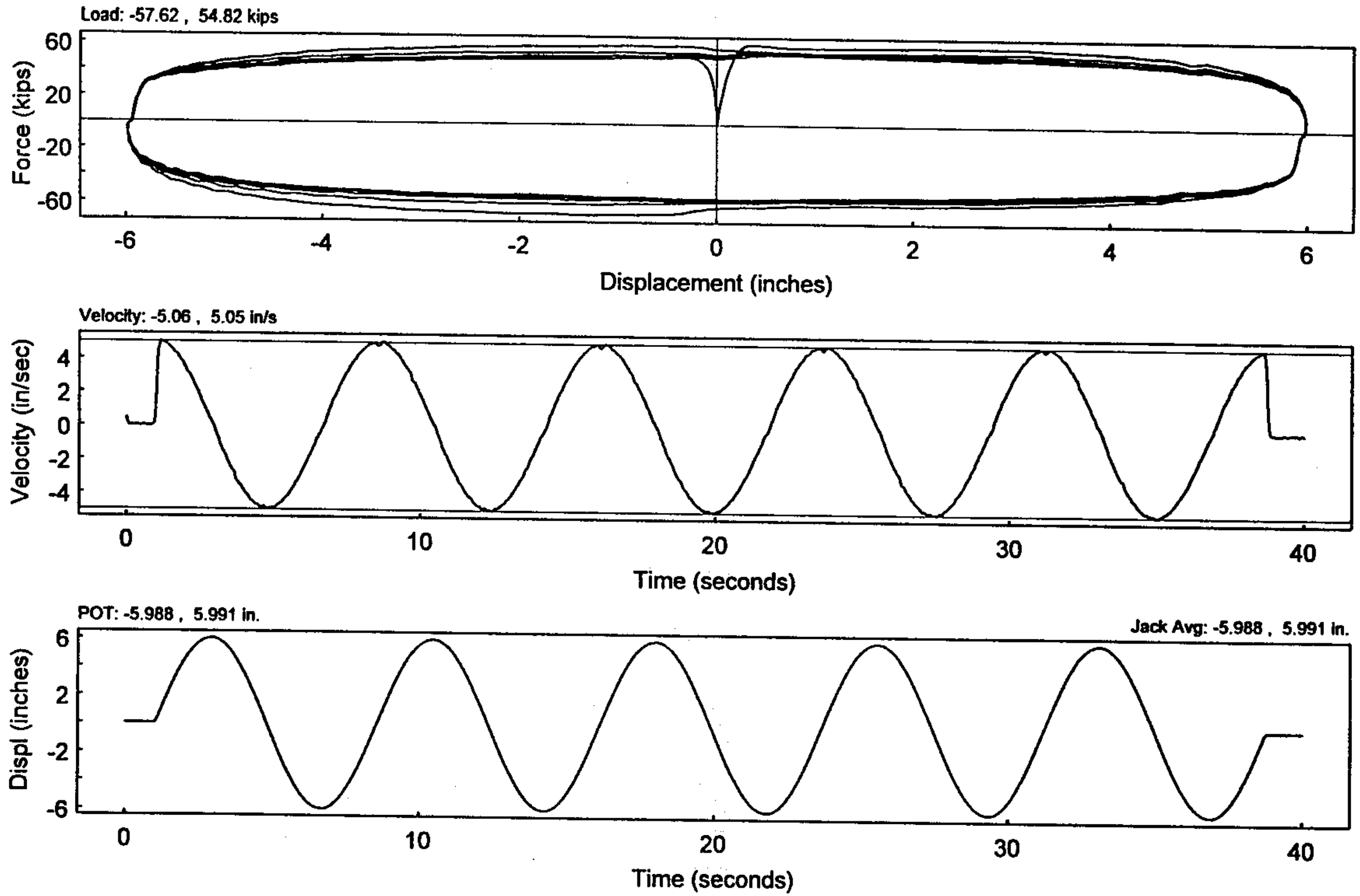
Damper: C

Test: sinc16
Target Velocity: 10 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 21:15:49 1995
Function: cvplot.s

File: 950515.10



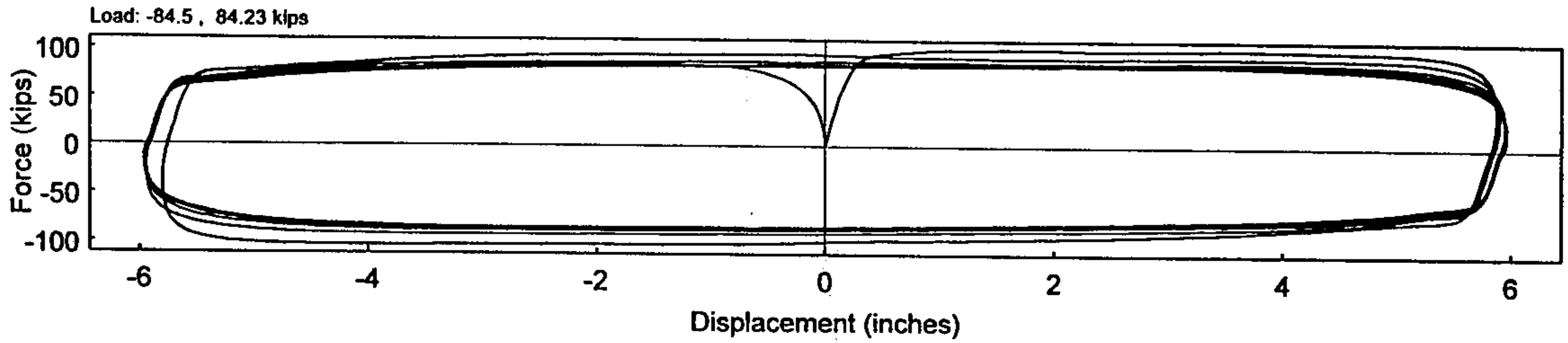
Damper: C

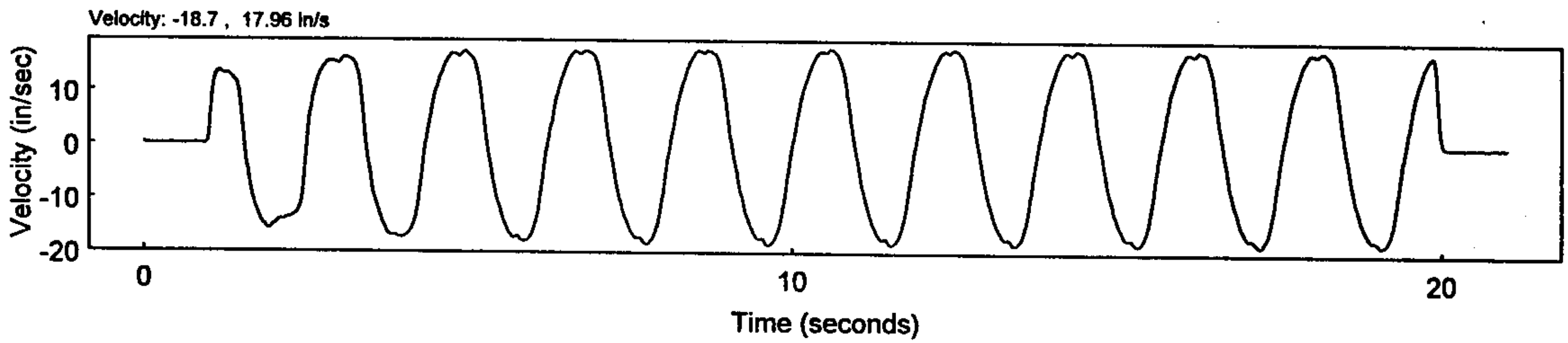
Test: sinc17
Target Velocity: 5 in/sec

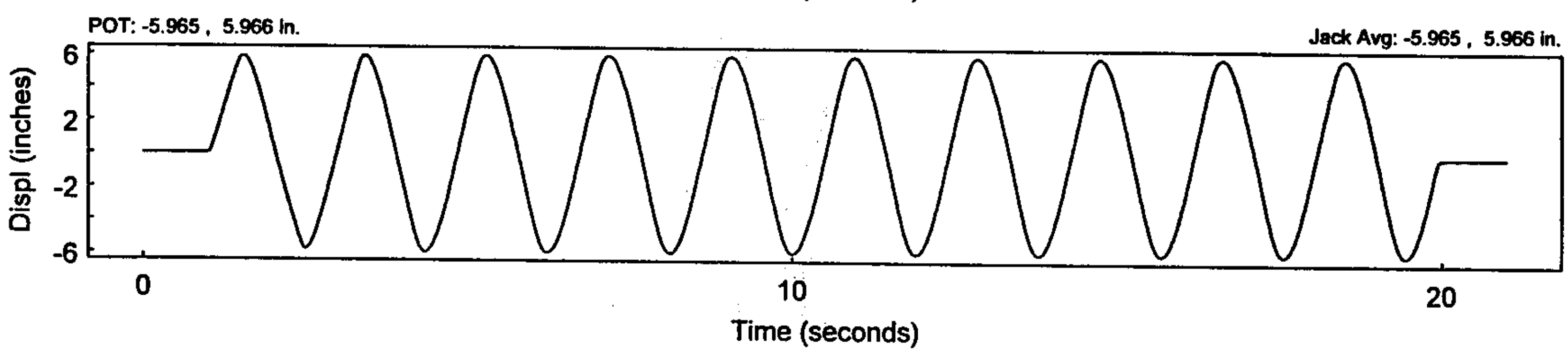
Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 21:16:55 1995
Function: cvplot.s

File: 950515.11







Damper: C

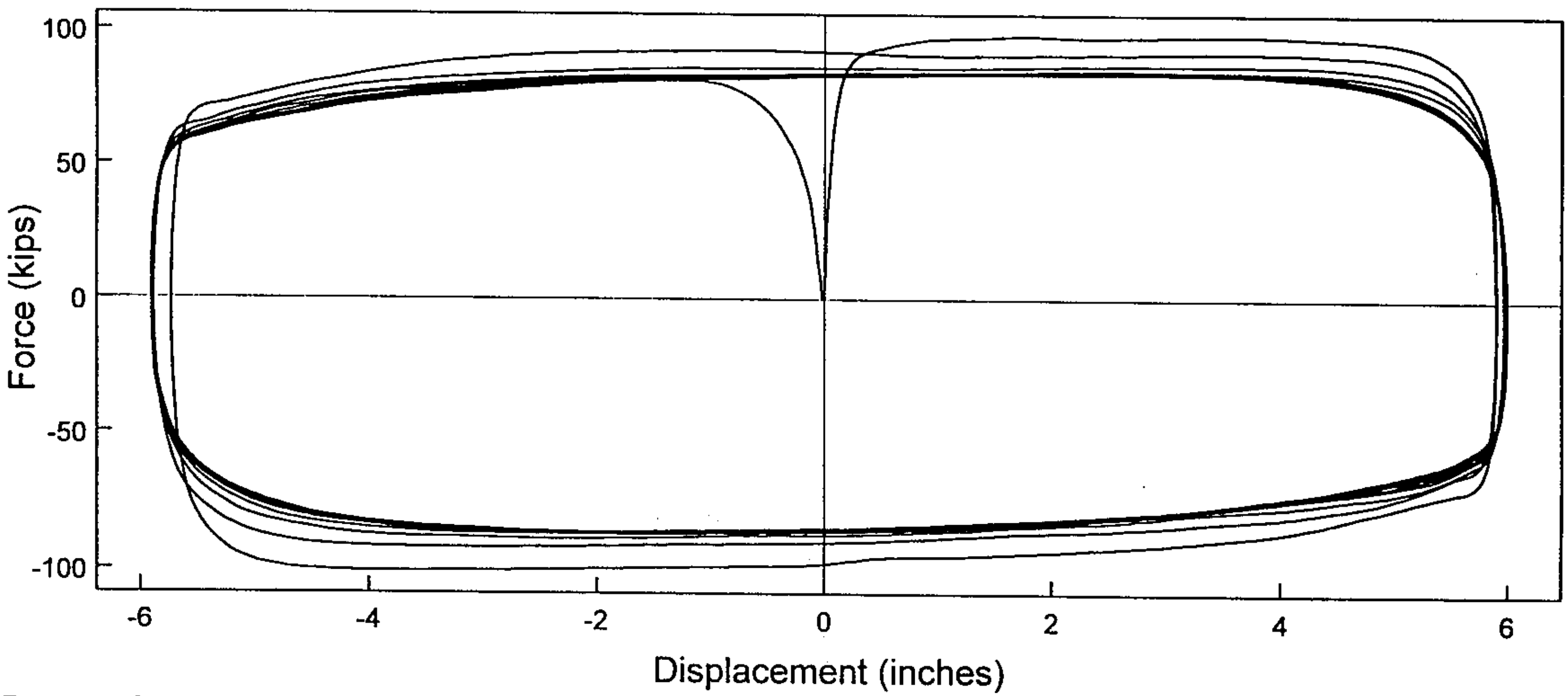
Test: sinc15
Target Velocity: 20 in/sec

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Sun Jun 11 21:18:09 1995
Function: cvplot.s

File: 950515.12

	Loop 2	Loop 3	Loop 4
Fmax, Fmin [kips]	91.66 , -92.38	86.73 , -89.24	84.62 , -87.44
Dmax, Dmin [in.]	5.9 , -5.89	5.96 , -5.9	5.97 , -5.9
Aloop, Abox [k-in.]	1996 , 2169.3	1919 , 2087.1	1881.3 , 2042.6
Efficiency [%]	92	91.9	92.1



Damper: C

Test: sinc15

Golden Gate Bridge Viscous Damper Pre-Qualification Tests

Plotted:Fri Oct 27 22:42:01 1995
Function: edplot.s

File: 950516.02

Appendix C

Testing/Pre-Qualification Program for Model Dampers

VISCOUS DAMPER TESTING/PREQUALIFICATION PROGRAM

PREQUALIFICATION OF DAMPERS

Bids for dampers on the suspension bridge will only be accepted on *prequalified* dampers. Dampers will be prequalified on the basis of testing conducted at the Earthquake Engineering Research Center[1] for TYLI/IAI and the Golden Gate Bridge District, and on the basis of a written proposal.

Damper Evaluation Panel

A Damper Evaluation Panel has been established to review the test results and written proposals from manufacturers. The DEP will prequalify dampers for bidding. The members of the DEP are:

Tim Ingham (chair)	TYLI
David Liu	IAI
James Kelly	Consultant to TYLI/IAI
Jerry Kao	GGH&TD
Roland Nimis	FHA
Moshen Sultan	Caltrans

Fees, Retesting, Delivery, Etc.

The testing program is being funded by the Bridge District, but manufacturers are expected to provide dampers for the testing program at no charge to TYLI/IAI or the Bridge District.

Only one damper may be submitted for testing. Retesting of failed dampers will not be performed.

At the request (and expense) of the manufacturer, adjustments to the dampers (to the orifices, valving, etc.) may be made after initial testing, in order to fine tune the response. Four weeks will be allowed for the adjustment, including shipping to and from the EERC. A fee of $4000 will be charged for repeat of the initial testing.

GENERAL REQUIREMENTS FOR DAMPERS

[1]of the University of California, Berkeley.

Viscous type dampers are required for the seismic retrofit of the suspension bridge. Detailed technical requirements for the dampers are described in the attached "Technical Requirements for Dampers." The most important parameters of the dampers are:

Size of Dampers

- Peak Force = 650 kips
- Peak Velocity = 75 in/sec
- Stroke = ±24 inch
- Energy Absorption = 22500 BTU in 90 seconds

Constitutive Law

Preferably, dampers shall have a constitutive law of the form:

$$F = 75\ \text{kip}\cdot\text{sec}^{1/2}/\text{in}^{1/2}\cdot V^{1/2}.$$

The constitutive law should be independent of the stroke position, and valid over the frequency range 0.1-5.0 Hz and the temperature range 40-125°F.

Alternative Constitutive Laws
Manufacturers may suggest alternative constitutive laws (*not* of the form $F=C\cdot V^{1/2}$) as appropriate to the nature of the proposed damper.

The proposed damper must dissipate energy during seismic excitation similarly to the specified damper (constitutive law), without a large increase in the peak damper force. TYLI/IAI will test (analytically) any suggested alternative constitutive relationship. Manufacturers are requested to wait for the results of (and conclusions from) the analysis before building the orificing and/or valving for the model dampers.

MODEL DAMPERS

Model dampers shall be as follows:

Capacity of Laboratory

Testing will be conducted at the Earthquake Engineering Research Center of the University of California, Berkeley. Model dampers shall be designed to fit into the EERC test rig shown on the attached diagram. The capacity of the test rig is:

- Peak Force = 100 kips
- Peak Velocity = 20 in/sec
- Stroke = ±6 inch

Model dampers shall have bushings at each end to fit 2½ inch diameter pins.

Relationship between the Model and the Actual Dampers

In order for the test program to be a useful predictor of the performance of the dampers to be used in the seismic retrofit, the basic functioning of the model dampers and the actual dampers must be similar. Although this principle cannot be stated precisely, because the details of the dampers proposed by various manufacturers will vary, the following guidelines reflect the intention of the DEP:

Pressure
The ambient and operating pressures should be maintained between the model and the actual dampers, as nearly as possible. This is necessary because the behavior of the seals, orifices, etc. is pressure dependent.

Orifice(s)
The basic *design and functioning* of the orifice(s) should be maintained between the model and the actual dampers, as nearly as possible. Important physical parameters (e.g. fluid velocity through the orifice) should be maintained.

Seals
The basic *design and functioning* of the seals should be maintained between the model and the actual dampers; the same type and number (at least not more) of seals should be used.

Fluid
The type and grade of fluid should be maintained between the model and the actual dampers.

Overall Configuration
The overall configuration of the model damper should be similar to that of the actual dampers. Practical simplifications may be made to the model damper, e.g., the material may be different, but the design and functioning of the model damper should be as similar as possible to that of the actual dampers.

The selected manufacturer will be required to certify that the actual dampers are of similar design to the model damper, when the actual dampers are delivered.

Constitutive Law

Preferably, model dampers should have a constitutive law of the form:

$$F = 22.4\ \text{kip}\cdot\text{sec}^{1/2}/\text{in}^{1/2}\cdot V^{1/2}.$$

This constitutive relationship is consistent with the peak force and velocity requirements of the test rig. The similitude requirements given under "Relationship between the Model and the

Actual Dampers" take precedence over this requirement, however, if the two are in any way contradictory.

Scaling Laws

Manufacturers shall provide the scaling laws (how test velocity, force, etc. relate to actual velocity, force, etc.) for the dampers, considering the basic physics governing their operation. These laws are critically important in sizing the model dampers and interpreting the test results. Manufacturers are responsible for correctly sizing the model dampers, according to the scaling laws.

The temperature dependence of the devices shall also be provided (i.e., changes in the constitutive law between 40°F and 125°F).

Ownership of Model Dampers

Model dampers shall be delivered to the EERC by the manufactures. After testing, the dampers will remain the property of the manufacturers. If requested, they will be returned to the manufacturers at their expense.

The dampers should be set aside for possible future testing conducted as part of the supply of the actual dampers.

Details of the model dampers will be kept confidential by TYLI/IAI, the EERC, and the DEP.

TEST PROGRAM

Initial Testing

A subset of the cyclic testing described below will be performed first. These tests will serve as a benchmark against which the cyclic testing may be compared, to determine the effect of prolonged cycling (due to wind excitation). See the attached schedule of tests A.

Testing for Wind Excitation

The dampers will first be tested to verify the longevity of the seals under wind excitation. The main test parameters will be:

- Peak Force = Low
- Peak Velocity = 0.5 in/sec
- Stroke = ±6 inch
- Frequency = 0.02 Hz
- Cycles = 1,800
- Temperature = laboratory ambient temperature

A lateral load will be applied to the damper during the wind testing, to simulate the gravity load on the actual damper. The lateral load will be set equal to the ratio of bearing area between the model and the actual damper times the anticipated weight of the actual damper. Manufacturers shall state the anticipated weight of the actual damper and provide the lateral load to be applied to the model damper.

Measurements Taken
The following parameters will be recorded (every 100th cycle):

- Displacement Input
- Force Output
- Laboratory Ambient Temperature
- Damper External Temperature

The damper will be positioned so that any fluid leaking from the dampers can be collected.

Acceptance Criteria
The dampers will be considered to have passed the test if there is no observed (or very small) fluid loss and no evidence of seal degradation. The dampers will not be taken apart to inspect the seals, however.

Cyclic Testing

The main cyclic testing will be conducted after the wind testing. The main test parameters will be:

- Peak Force = 0-100 kips
- Peak Velocity = 0-20 in/sec
- Stroke = ±0-±6 inch
- Frequency = 0.1-5.0 Hz.
- Cycles = 5-10, square wave (velocity) and sinusoidal input
- Temperature = 40°F, 70°F, 125°F

See the attached schedule of tests C. The test dampers will be reconditioned (allowed to cool to the specified test temperature) whenever the energy input exceeds about 10,000 in-kip.

A lateral load will be applied to the damper during the energy dissipation and endurance test at 20 in/sec velocity and ±6 inch stroke; to simulate the gravity load on the actual damper.

Measurements Taken
The following parameters will be recorded:

- Displacement Input
- Force Output

- Laboratory Ambient Temperature
- Damper External Temperature

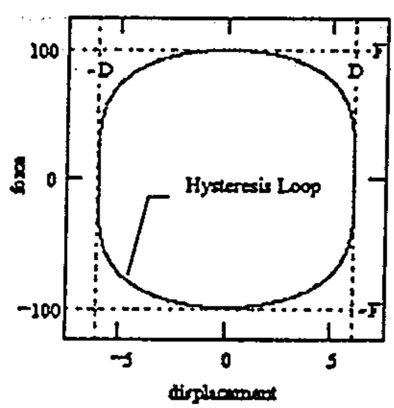
Acceptance Criteria

The dampers will be considered to have passed the test program if:

- The force-velocity response matches the constitutive law prediction within ±15%, for strokes greater than 10% of full stroke, over the full range of frequency, and at 40°F, 70°F, and 125°F, for all test cycles. Square wave tests at constant velocity will be used to determine the force-velocity response.

- The (static) damper friction force does not exceed 2½% of the damper capacity (100 kips).

- The force developed by the dampers is primarily dissipative. The area of the damper force-displacement hysteresis loops shall be at least 82½%[2] of the rectangular area defined by the peak force and the peak displacement, for strokes greater than 25% of full stroke, over the full range of frequency, and at 40°F, 70°F, and 125°F, (with each cycle considered independently):



Sinusoidal tests will be used to measure energy dissipation.

Time History Input

The dampers will also be driven with a time history displacement input scaled from the global analysis of the bridge. See the attached plot "Time History Input" of *displacement input* and expected response. This test is for information only.

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[2]The theoretical efficiency of an $F = C \cdot V^{1/2}$ damper is 87½%.

Publication

At the discretion of the manufacturers, the test results and general conclusions may be published in an EERC report and made public. Manufacturers will given the opportunity to review the manuscript before publication to ensure that no proprietary information is divulged.

WRITTEN PROPOSAL

Manufacturers shall also submit written proposals describing the dampers to be used in the bridge retrofit. These shall describe the characteristics and functioning of the *actual* dampers.

The quality and completeness of the proposals will be a factor in selecting manufacturers and dampers for prequalification. Proposals which do not address all of the issues involved and offer solutions to the problems identified below and in the attached technical requirements will cause the dampers to be not qualified. The content of the proposals will be kept confidential by TYLI/IAI, the District, and the DEP.

The proposals shall address the following items:

Description of Company and Experience in Seismic Isolation and/or Energy Dissipation
The history of the proposed dampers should be given. Similar devices used in the past should be identified and the similarity of those devices to the proposed dampers described. Any available documentation of the field performance of those devices should be supplied.

If possible, three owner references for similar devices shall be given. Three owner references for the *seal type and design* to be used in the dampers shall be given (these may be the same as the above). Bridge project references should be given, if available.

General Description of Proposed Damper, Including Major Elements and General Functioning, Schematic Drawing of Damper
A general description of the proposed damper shall be given. Its basic operation shall be described, and the basic operation and functioning of the orifice(s) and seals described.

Constitutive Law of Damper–Force-Velocity Relationship, Temperature Sensitivity
The force-velocity relationship of the damper shall be stated, from 0-75 in/sec velocity. Any deviation from the law (e.g., at low velocity) shall be stated. Any other component of the constitutive law (i.e., a stiffness term) shall be stated also.

The variation of the force-velocity relationship with temperature shall be given, from 40-125°F.

Materials - Corrosion Resistance, Durability of Dampers in a Marine Environment
The materials of the damper shall be described (i.e., the grade of stainless steel), and their resistance to corrosion in a marine environment discussed.

The means of protection of the piston rod against corrosion shall be described (positive means of protection are required). The means of protection against corrosion of the interior of the damper shall be described (how is moisture kept out of the damper?) (positive means are required).

Supporting evidence of the corrosion resistance of the damper design and materials used should be given.

Longevity of Seals under Wind and Traffic Excitation, Supporting Evidence Thereof
A discussion of the longevity of the seals under wind excitation is required. Supporting evidence of the performance of the seals (other than the TYLI/IAI/EERC test) should be given.

A discussion of the longevity of the seals under traffic vibration of the dampers is required. Supporting evidence of the ability of the seals to tolerate the imposed vibrations shall be given, or a means of isolating the seals from the vibrations should be described.

These issues are considered to be critically important by TYLI/IAI and the DEP. Convincing solutions to these problems are a prerequisite to prequalification.

Inspection and Maintenance Needs of Dampers
The inspection and maintenance needs of the dampers shall be described (these shall be minimal). The means to inspect and maintain the dampers shall be described also.

Energy Dissipation Calculations for Seismic Excitation
Calculations of the temperature rise of the dampers during seismic excitation shall be given, based on the energy absorption requirements given in the attached technical requirements. The effect of the temperature rise on the functioning of the dampers shall be discussed.

Supportive (Previous) Test Data
Any supporting data from previous tests of similar devices shall be submitted.

Sample Specification for Dampers (Optional)
Manufacturers may wish to submit sample specifications for similar devices used in the past. These may be helpful to TYLI/IAI when writing the project specifications.

Note

Only *preliminary* designs and calculations are required in response to these issues. The designs and calculations must convincingly support the proposed solutions, however.

BIDDING POLICIES

The following paragraphs summarize the bidding policies of the District, under which dampers will be purchased for the seismic retrofit of the suspension bridge. These policies are still tentative, and subject to change.

Bidding

Dampers must be prequalified for bidding. The selection of dampers will be by competitive bid, on prequalified dampers only.

Buy America Provisions
The determination of the *low bid* will include a "Buy America" provision. A bid based on dampers manufactured from foreign steel shall be 25% (of the domestic bid) less than a bid based on dampers manufactured from domestic steel in order to be successful.

A "damper manufactured from domestic steel" is one that is made from domestic steel, with all fabrication and finishing processes carried out in the United States. A "damper manufactured from foreign steel" is one that is made from foreign steel, or fabricated or finished outside of the United States.

Separate Damper Contract
In order to simplify the application of the Buy America provision, dampers will be purchased by a separate contract, independent of the rest of the suspension bridge retrofit. Manufacturers will be required to put up a performance bond for 110% of the value of the damper contract.

Installation of Dampers
Dampers will be turned over to the general contractor for installation, the manufacturer will be required to provide a damper installation manual, equipment to change the length of the dampers[3] and make other necessary field adjustments, and technical assistance for installation of the dampers.

Warranty of Dampers

The manufacturer will be required to warranty the dampers against defects in materials and workmanship for a period of five years beyond the date of *installation*. Dampers which fail in service (more than an insignificant leakage of fluid, or obvious seal degradation) will have to be (removed if necessary and) repaired at the manufacturers expense.

As part of the supply of the dampers, the manufacutre will be required to supply the tools and equipment needed to inspect and maintain the dampers.

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[3]Thermal movements of the bridge make its exact position uncertain.

Appendix D

Technical Requirements for Full-Size Dampers

TECHNICAL REQUIREMENTS FOR DAMPERS

Constitutive Law

Dampers with a constitutive law

$$F = 75\ \text{kip}\cdot\text{sec}^{1/2}/\text{in}^{1/2}\cdot V^{1/2}$$

are required. Two dampers per chord of the stiffening truss will be used for a total of 48 dampers longitudinally. Two dampers will be used transversely to isolate the bridge from the South Pylon, for a total of 50 dampers.

The damper force shall be within ±15% of the constitutive law prediction over the ranges of stroke and frequency given below and between 40° and 125°F temperature.

Seismic Excitation

The relationship of the dampers to the overall seismic retrofit design is described in the Suspension Bridge Strategy Report. The technical requirements given herein are based on a second optimization study not described in the Strategy Report.

For seismic excitation, the requirements for the longitudinal dampers are

Table 1, Seismic Requirements for Longitudinal Dampers (48 reqd.)

Parameter	Value	Note
Constitutive Law	$F = C \cdot V^n$	
Coefficient, C	75 kip·sec$^{1/2}$/in$^{1/2}$	
Exponent, n	½	Best for both seismic and wind excitation.
Stroke	±24 inches	Peak value
Velocity	75 in/sec	Peak value
Acceleration	650 in/sec^2	Peak value
Force	650 kips	Peak value
Peak power	7250 horsepower	Extreme peak value, see figures
Average power	350 horsepower (261 kilowatts)	Maximum value
Energy Dissipated	22500 BTU (2.37×10^7 Joules) (6.59 kilowatt-hours)	Maximum value
Duration of Motion	90 seconds	SA2 record
Frequency	0.1-5.0 Hz	Excitation is from the side and main spans, and the towers
Ambient Temperature	40-100°F	Less than the full temperature range for the bridge design

The requirements for the transverse dampers are

Table 2, Seismic Requirements for Transverse Dampers (2 reqd.)		
Parameter	**Value**	**Note**
Constitutive Law	$F = C \cdot V^n$	
Coefficient, C	75 kip·sec^{½}/in^{½}	
Exponent, n	½	
Stroke	**±24 inches**	Peak value (Add ±4 inches for thermal excitation)
Velocity	75 in/sec	Peak value
Acceleration	**1000 in/sec^2**	Peak value
Force	650 kips	Peak value
Peak power	7500 horsepower	Extreme peak value, see figures
Average power	**475 horsepower (354 kilowatts)**	Maximum value
Energy Dissipated	**30000 BTU (3.16×10^7 Joules) (8.79 kilowatt-hours)**	Maximum value
Duration of Motion	90 seconds	SA2 record
Frequency	0.1-5.0 Hz	
Ambient Temperature	40-100°F	Less than the full temperature range for the bridge design

Values in boldface are more severe than for the longitudinal dampers.

A series of time history and hysteresis plots is attached. The plots are for the most severely loaded dampers (of eight) at each of the six locations of the longitudinal dampers, and for the most severely loaded of the transverse dampers at the South Pylon.

Wind Excitation

The requirements for wind excitation are based on a study of the effect of the dampers on the buffeting of the bridge. The study showed that dampers with exponents $n < 1$ dramatically reduce the buffeting response of the bridge. The demands on the dampers are then small.

For wind excitation, the requirements for the longitudinal dampers (between the main span and the towers only) are

Table 3, Wind Requirements for Longitudinal Dampers

Parameter	Value	Note
Stroke	±3 inches	Peak value
Accumulated Stroke	1200 inches (100 feet)	Over assumed length of storm
Velocity	1 in/sec	Nominal value
Acceleration	1 in/sec^2	Nominal value
Force	75 kips	Peak value
Peak power	10 horsepower	Peak value
Average power	1 horsepower (0.75 kilowatts)	Nominal value
Energy Dissipated	4500 BTU (4.75×10^6 Joules) (1.32 kilowatt-hours)	Over assumed length of storm
Duration of Motion	3 hours	Assumed length of storm (conservative)
Frequency	< 1 Hz	Excitation is from the side and main spans, and the towers

The most important effect of wind excitation of the dampers would appear to be the accumulated stroke on the seals, and the potential for wear. Assuming one storm per year over the 40-year life of the dampers, the lifetime accumulated stroke is (about) 50,000 inches.

[The buffeting study assumed the constitutive law of the dampers, $F = 75\ \text{kip}\cdot\text{sec}^{1/2}/\text{in}^{1/2}\cdot V^{1/2}$, to hold at small velocities. If damper manufacturers will suggest force-velocity relationships more appropriate for the above range of velocity, the study can be repeated easily.]

Thermal Excitation

The dampers should be insensitive to ambient temperature, between 40°F and 125°F. The effects of changes in the properties of the dampers with ambient temperature must be accommodated within the tolerance for damper performance, stated above.

The dampers must also accommodate the seasonal thermal movement of the bridge (with additional stroke beyond that required for the sesimic excitation). This is ±4 inches between the main span and the towers.

Traffic Excitation

The dampers may also be subjected to small amplitude (say, 0.01-0.001 inch), high frequency (say, 10-100 Hz) vibrations caused by traffic on the bridge. Unless it can be shown that the damper seals will tolerate this excitation, the dampers must be "isolated" from this excitation.

Position

The dampers will be installed in a horizontal position. The side (gravity) loading on the dampers must be reflected in their detailed design.

The dynamic loading of the dampers due to vertical excitation shall also be considered. Equivalent static forces on the dampers may be derived from the response spectrum for vertical excitation (attached), as a function of the natural frequency of vibration of the dampers themselves.

Materials, Corrosion Resistance

Because the dampers will be installed in a marine environment, maximum resistance to corrosion is required. *The dampers should be largely stainless steel (including even plated piston rods).* Selected parts and components may be of other materials, but the burden of proof is on the manufacturer to show that the corrosion resistance of these parts is equivalent to stainless steel (or that they are otherwise protected).

The grade of stainless steel to be used is left to the discretion of the manufacturer, considering corrosion resistance, strength, machinability, etc.

Damper fluids should be environmentally safe, and non-flammable.

Longevity, Inspection, and Maintenance

The intended life-span of the seismic retrofit is 40 years. Dampers shall be designed to have a useful life of 40 years.

Inspection of the dampers after installation will probably be possible, on an annual, or bi-annual basis. Provision should be made to monitor the damper fluid pressure or level, as appropriate to the damper design.

Field maintenance of the dampers will be difficult. The dampers should be designed to be virtually maintenance free. If necessary, a program of factory maintenance at long intervals–every 10-20 years–can be planned.

Testing

A testing/prequalification program will be conducted by TYLI/IAI, the Bridge District, and the EERC, as described in the attached notes.

The dampers supplied for installation will also be tested. Drop testing will be conducted if a hydraulic testing facility of sufficient capacity cannot be located. The model dampers will then also be drop tested, to relate the cyclic testing of the model dampers to the actual dampers.