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DYNAMIC RESPONSE OF TWO VISCOELASTIC DAMPERS

Report to Santa Clara County

BY

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by

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Report to

County of Santa Clara
Construction Services Division

University of California at Berkeley
Department of Civil Engineering

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ACKNOWLEDGEMENTS

This test program was conducted by the Department of Civil Engineering of the University of California at Berkeley under Service to Industry Program Project No. ES-2046. The County of Santa Clara sponsored the project.

Professor James M. Kelly was the Principal Investigator.

Mark Troxell was in charge of specimen setup. Bill MacCracken operated the 300 kip Universal Testing Machine and calibrated the instrumentation. Todd Merport verified all electronic components and programmed and operated the data acquisition and control system. Hany Khechfe took photographs and videotaped the tests. Todd Merport and Hany Khechfe also assisted in the production of this report.

1 INTRODUCTION

This report summarizes the results of a test program on the dynamic response of two structural dampers. These devices are based on Polymer 109, a viscoelastic (VE) material manufactured by 3M Corporation of St. Paul, Minnesota. The test specimens were manufactured by 3M. They are reduced scale models of structural dampers to be installed in a building in Santa Clara County. The test program was sponsored by the County of Santa Clara, under the advise of The Crosby Group of Redwood City, California. The Crosby Group is the engineering firm in charge of the design of the structural dampers.

The experimental work was conducted by the Department of Civil Engineering of the University of California at Berkeley. The tests were performed on June 10 and 11, 1993, and were witnessed by John Rosenbrock, P.E., Project Manager of Santa Clara County, Kenneth Campbell, Project Engineer of The Crosby Group, and Dr. Ming-Lai Lai, Senior Mechanical Engineer of 3M Corporation.

2 OBJECTIVES

The test program had two objectives. The first objective was to determine whether the dampers could be subjected to the strain levels expected to occur under extreme earthquake conditions without suffering any damage. The second objective was to verify the mechanical properties of the material used in their design.

3 TEST PROGRAM

Earthquake response

The dampers were subjected to dynamic conditions corresponding to the following levels of seismic demand:

Service Level Earthquake: 0.1g Loma Prieta.
Design Base Earthquake: 0.34g Loma Prieta.
Maximum Credible Earthquake: 0.4g Loma Prieta.

The Crosby Group generated a computer model of the building which included the viscoelastic dampers and analyzed the response of the structure under one of the ground motions. The structural response corresponding to the other two excitation levels was computed by scaling the previous results, i.e, assuming linear elastic response. The displacement time histories of the dampers computed for each of the selected ground motions were then used as command signal for the experiments.

Mechanical properties

The mechanical properties of VE materials under shear conditions are characterized by two shear moduli: the storage modulus G' and the loss modulus G" [1, 2]. These values can be determined from the material shear response to sinusoidal input. It is well known, however, that the values of G' and G" are temperature, frequency, and amplitude dependent. Furthermore, under dynamic loading, energy dissipation occurs mainly through heating of the material which in turn affects its mechanical properties.

To estimate G' and G", the specimens were subjected to harmonic excitation consisting of 3 cycles of displacement at a frequency of 0.5 Hz and at amplitudes of 0.1, 0.2, 0.5, and 0.8 inches. After these tests, the dampers were subjected to 10 cycles of harmonic displacements with an amplitude of 1 inch, also at 0.5 Hz. This would represent conditions significantly more severe than those expected during the Maximum Credible Earthquake. Finally, the first cyclic test (at 0.1 inch amplitude) was repeated after the dampers cooled down, to verify whether the VE material could fully recover its mechanical properties after the test under extreme conditions.

Table 1 below summarizes the testing program. All tests were performed at room temperature. 68°F The testing machine was operated under displacement control.

Table 1. Test Matrix

TEST TYPE	Maximum Displacement	Test ID
Service Level EQ	0.235"	eq02
Design Level EQ	0.800"	eq08
Max Credible EQ	1.000"	eq10
Harmonic 3 Cycles	0.1"	h301
Harmonic 3 Cycles	0.2"	h302
Harmonic 3 Cycles	0.5"	h305
Harmonic 3 Cycles	0.8"	h308
Harmonic 10 Cycles	1.0"	h1010
Harmonic 3 Cycles	0.1"	h301a

Additional Testing: Failure Mode

An additional test program was carried out at the University, at the request of the Principal Investigator. It consisted of testing to failure several small dampers made with Polymer 109. These smaller specimens were subjected to increasing displacements (ramp tests) at different displacement rates. Shear failure occurred at strain levels varying from 300% to up to 400%. The corresponding strain rates varied from 3.44 in/in/sec down to 0.2 in/in/sec. No bond failure was observed: failure always occurred through the viscoelastic material. Room temperature varied from 23° C to 25° C. The report of this testing program is presented in Appendix B.

4 TEST SETUP & INSTRUMENTATION

The dampers basically consisted of three elements: an inner steel tube with square cross section, an outer steel member, and four VE pads connecting these elements. The inner tube was able to move longitudinally inside the outer element, forcing the VE pads to deform in shear. The pads consisted of two rectangular pieces (6"x½"x12") of Polymer 109, with a steel plate ¼" thick epoxied between them. Figure 1 shows schematically the main characteristics of the dampers. Figure 2 includes part of the construction drawings provided by The Crosby Group that show the longitudinal and cross section of the dampers. Notice the safety device (bolt sliding inside slotted hole) to prevent the dampers from deforming more than 1 inch.

The length of the specimens (in their undeformed configuration) was 43.5 inches. The inner tube was 8"x8"x½." The end plates measured 14"x14"x2". The total shear area of the VE material was 4 pads x 6" x 12" = 288 in^2. The effective thickness of each pad was 1 inch.

Both dampers were tested on the 300 kip Universal Testing Machine existing at the Structural Dynamics Laboratory in 145 Davis Hall. The end plates of the specimens were connected to the actuator piston and the upper crosshead with four 1" high strength bolts. Large clamps were also used to provide additional safety.

The applied load was measured with the 300-kip load cell attached to the crosshead of the testing machine. Load readings are accurate to ±0.1 kip. Specimen displacement was measured with the LVDT existing inside the actuator's piston. The accuracy of this instrument is better than ±0.01". The temperature of the VE material was measured with a thermocouple placed inside one of the VE pads. Temperature readings are accurate within ±0.1°C. Room temperature was measured with a second thermocouple, with an accuracy of ±0.5°C.

Figure 3 presents photographs of the test setup and a "close up" of one of the VE pads. Notice the thermocouple wire inserted in the VE material.

The data acquisition and control system consisted of a Metrabyte DAS 1601 card installed in a 50 MHz 486 PC running under the QNX operating system. The Autonet program was used to collect the experimental data and provide the command signal to control the actuator of the testing machine.

5 TEST EXECUTION & DATA PROCESSING

Test execution

Damper 2 was tested on June 10, 1993. Damper 1 was tested the following day. The tests were performed following the sequence indicated in the test matrix (Table 1). Room temperature varied between 24°C and 25°C. The Autonet system was configured to send the command signal to the dynamic actuator, read all the instruments, convert the readings to appropriate engineering units, and save all data in binary (Autonet LDF) format.

The instrumentation was scanned at an interval of 0.02 seconds, i.e. 50 readings were taken each second. Data acquisition always started 15 seconds before sending the command signal in order to have time to abort the test in the event of any erroneous, unusual, or dangerous situation. The dampers were left to cool down to their initial temperature before starting a new test.

Data processing

After each test, the experimental data was backed up on floppy disks in LDF format, and hard copy plots of the displacement time history, temperature time history, and force versus deformation were generated.

All the datafiles were then transferred to DOS diskettes in text format, for further analysis. Data processing was done using the S language [3], an interactive programming language for data analysis and graphics.

The following procedure was used to process the experimental data:

- Discard the first 15 seconds of readings.
- Remove initial offsets from load and displacement records.
- Estimate the applied displacement rate (velocity) by numerical differentiation of the displacement record.
- Estimate the external energy supplied to the system by numerical integration of the load times the velocity.
- Generate time history plots of command signal, displacement, velocity, load, temperature (including room temperature), and energy.
- Generate XY plots of load versus displacement and temperature versus energy (including linear least square fit $T = T_0 + \beta E$)

The mechanical properties of the VE dampers were estimated from the harmonic tests as follows:

- Compute average shear stress and shear strain time histories.
- Discard first half and (at least) last half cycles of data, to remove transient response components. Reverse sign of stress and strain for convenience during subsequent processing.
- Using nonlinear least squares (NLS) techniques, fit an equation of the form $\gamma(t) = \gamma_0 \sin(\omega t)$ to the shear strain data, where $\omega = 2 \pi f = \pi$ rad/sec is the circular frequency of the excitation.
- Using NLS, fit an equation of the form $\tau(t) = \tau_0 e^{-\alpha t} \sin(\omega t + \delta)$ to the shear stress data. The exponential term is used to model the softening of the material due to the temperature raise. The loss factor $\eta = \tan\delta = G''/G'$ characterizes the damping of the VE material [3].
- Estimate the absolute value of the shear complex modulus as $|G^*(t)| = (\tau_0/\gamma_0)\, e^{-\alpha t}$
- Estimate the storage and loss shear moduli as $G'(t) = |G^*(t)| \cos\delta = G'\, e^{-\alpha t}$ and $G''(t) = |G^*(t)| \sin\delta = G''\, e^{-\alpha t}$
- Generate time history plots of shear stress, shear strain (including fitted equations), and storage and loss shear moduli.
- Generate XY plots of stress versus strain (including fitted equations) and shear moduli versus temperature, including equations, fitted via linear least squares, of the form $G'(T) = G'_0 - k'\,T$ and $G''(T) = G''_0 - k''\,T$

6 *TEST RESULTS*

Both dampers had similar behavior when subjected to the same input. The response to excitations with the same waveform but different amplitudes was consistent. The discussion of the dynamic response of the dampers therefore will be based on the experimental results from selected tests. Appendix A contains all the graphical and numerical information generated for each damper during each test.

To summarize the experimental measurements, Table 2 presents peak values of displacement and load obtained during each test, as well as the initial temperature of the VE material and the increase in temperature due to energy dissipation. The values estimated for the shear storage modulus G', the shear loss modulus G", and the loss factor η are presented in Table 3. Table 4 compares the average estimated mechanical properties with the corresponding values found in the Polymer 109 Database available from 3M Corporation. In these three tables, values for tests h301a (3 cycles at 0.1") are presented after those of tests h310 to facilitate comparisons, even though tests h301a were performed after the 10 cycle tests h1010.

Earthquake response

Figure 4 shows the response of Dampers 1 and 2 (D1 and D2) to the Maximum Credible Earthquake (MCE). Figures 4a1 and 4a2 indicate that the actuator reproduced the command signal reasonably well, although it was not able to follow its high frequency components, due probably to the high damping of the test specimens.

Both dampers showed almost identical displacement responses. Peak displacement was in both cases 0.95" which is 5% lower that the target 1" displacement. Load responses were also very similar. Peak load for D1 was about 5% lower than that for D2 (71 vs 74 kips). The force versus displacement plots (Figures 4b1 and 4b2) demonstrate the excellent energy dissipation characteristics of the dampers. They both display several full hysteresis loops occurring during the time of peak seismic demand.

D1 became 6°C warmer after the earthquake test; D2 temperature increased 7°C. As expected, temperature increase is well correlated with the energy supplied to the specimens. The temperature versus energy plots (Figures 4b1 and 4b2) show that temperature can be approximated reasonably well as a linear function of energy input ($T = T_0 + \beta E$). Assuming that all input energy is converted into heat, and that there are no heat losses, $\beta = 1/(Ms)$, where M is the mass of VE material, and *s* is its specific heat. The oscillations in the energy data are due to interchanges between elastic and kinetic energy within the VE material during each cycle of deformation.

The slope of the T-E curve computed for D1 is slightly smaller than that computed for D2 (β_1 = 0.0135, β_2 = 0.0157). This could be caused by small differences in the properties of the material used to make each damper. (A value of β = 0.0123 is obtained from the published data for this material [2] using s = 0.44 cal/gram°C and mass density ρ = 1.06 gram/cm^3, after appropriate unit conversions.)

The behavior of the dampers during the smaller amplitude earthquake tests was consistent with that observed for the MCE. Differences in the response of the two dampers during these tests were generally smaller than those found for the MCE tests.

Cyclic Response & Mechanical Properties (3 Cycle Tests)

The test at 0.8" amplitude was selected as representative of the 3 cycle tests at 0.5 Hz. Figure 5 presents all the information measured and calculated for the dampers. As in the case of the earthquake tests, the response was generally consistent and repeatable.

Figures 5a1 and 5a2 show that the displacement and load time histories measured for both specimens were very similar. Peak displacement for both dampers was 0.75", slightly lower than the target displacement of 0.8". Peak load of D1 was smaller than that of D2 (77.5 kips vs 87.0 kips). D1 was therefore slightly softer than D2. The force versus deformation plots obtained for D1 and D2 look very similar (Figures 5b1 and 5b2). Almost perfect elliptical hysteretic loops were formed during the time range from the end of the first half-cycle to the end of the command signal.

The slight differences in energy dissipation characteristics observed during the earthquake tests were also apparent in these cyclic tests: temperature rise for D1 was 5°C, whereas that of D2 was 6.3°C, consistently with the lower energy delivered to D1 by the actuator. The slopes of the fitted T-E curves were β_1 = 0.0122 and β_2 = 0.0151. Whereas β_1 is very close to the "theoretical" value β = 0.0123, β_2 is 23% larger.

Figures 5c1 and 5c2 graphically present the results of the procedure used to estimate the mechanical properties of the dampers. The correlation between the experimental data and the equations fitted via nonlinear least squares is excellent, proving the validity of the assumption of exponential decay of shear moduli of VE material under cyclic excitations. The stress-strain plots in Figures 5d1 and 5d2 also illustrate the agreement between measured and calculated data.

The initial value (after the first half cycle of deformation) estimated for the storage modulus G' for D1 is lower than that for D2 (G'_1= 200 psi, G'_2=240 psi). See Table 3. This is consistent with the previous observation about D1 being softer than D2 (lower forces at same displacement levels). The 3M Polymer 109 database for cyclic tests at 0.5 Hz, 80% shear strain, and 24°C temperature shows a value of G'=165 psi. The average estimated value of 220 psi is 33% higher than the value in the 3M database.

Table 4 indicates that this difference in storage moduli G' is smaller for all the other cyclic tests. The difference increases with the displacement (or shear strain) amplitude.

A similar situation occurs with the shear loss modulus, G". G''_1 is smaller than G''_2, but in this case the difference is 7% (Table 3). The average calculated value is, however, still 28% higher than the value in the 3M database. Again, this is the largest difference between estimated and published values of G", and the difference increases with the displacement amplitude.

The differences between the calculated and published shear moduli could be due to differences in specimen size and configuration (steel plate within VE material?), testing conditions, or to the numerical algorithm used to estimate the moduli from the experimental data. The estimates of G' and G" are somewhat sensitive to the range of data selected for the calculations.

Interestingly, the estimated loss factors $\eta = G''/G'$ are close for both dampers (η_1=1.5, η_2=1.4). The 3M database shows η = 1.47. As shown in Table 3, the differences in loss modulus computed from both dampers for all these tests are less than 7%. The average values of η are for all practical purposes equal to those in the 3M database.

Figures 5d1 and 5d2 also include plots of estimated shear moduli G' and G" versus measured temperature. These figures indicate that it is possible to model with reasonable accuracy the moduli as linear functions of temperature. As shown before, changes in temperature can also be estimated as linear functions of input energy. These observations could be used as basis for a scheme to compute the dynamic response of systems with VE material dampers.

10 Cycle 100% Shear Strain Tests

Figures 6a1 and 6a2 show response time histories for D1 and D2 under 10 cycles of 1" displacement at 0.5 Hz. As with previous tests, the achieved displacement amplitude was somewhat smaller than the command displacement (peak displacement was about 0.94" for both specimens).

The velocity records clearly indicate that the command signal was excessive for the servohydraulic actuator. The velocity waveforms were clipped at a peak velocity of about 2.8 in/sec. The theoretical peak velocity that the actuator is capable of providing, based on the capacity of the servovalve, is about 3.5 in/sec.

This distortion of the velocity response affected the load response of the specimen. The load time histories no longer appear as harmonic waveforms with exponential decay. This effect is also apparent in the load versus displacement plots presented in Figures 6b1 and 6b2. The curves are linear (instead of elliptical) in the small displacement (peak velocity) regions. Temperature increase was still reasonably approximated as a linear function of input energy.

The estimation of the mechanical properties of the VE material based on the 10-cycle tests can be visualized in Figures 6c1 and 6c2. The values of G' and G" computed for D1 and D2 are quite similar (within 10%, see Table 3). They are, however, still up to 25% larger than the values in the 3M database. The average loss factor is, as with the 3-cycle tests, equal to the value in the database (Table 4). Figures 6d1 and 6d2 show the measured and estimated stress-strain curves, and the shear moduli versus temperature curves.

Since the distortion in the load (and velocity) response was not apparent in the previous test (3-cycle 80% strain), and at the time there was no reasonable explanation for the change in response characteristics, it was decided to perform an extra 3-cycle test, with an amplitude of 0.9". This test was executed after the second 0.1" 3-cycle test for D1. The measured and calculated results are consisted with those of the main tests. The clipping in the velocity and the distortion in the load waveforms are incipient in this test. See Appendix A (test ID: d1h309).

Material Recovery Properties

The 10-cycle tests at 100% strain represented the most demanding dynamic conditions imposed on the dampers. To verify the ability of the VE material to recover its mechanical properties after having been subjected to such extreme demands, test h301 (3 cycles at 10% strain) was repeated after waiting for the VE material to cool down to a temperature close to that at the beginning of the first 3-cycle 0.1" test.

The behavior of the dampers during these tests was very similar to that observed during the first 3-cycle tests. Tables 2 and 3 show that damper 2 had almost identical response for both tests. Damper 1 showed a slightly lower peak load (11.6 kips) than that of the first test (13 kips). This represents a reduction in stiffness of about 10%. The computed values for the shear moduli were accordingly lower (260 psi vs 290 psi for G', 350 psi vs 390 psi for G"). Damper 1 was therefore slightly softer after the 10 cycle 100% shear strain test. The loss factor was, for all practical purposes, the same for both dampers and both tests.

No damage of any kind was observed in the dampers at the end of this experimental program.

REFERENCES

1. Ferry, John D., "Viscoelastic Properties of Polymers", John Wiley & Sons, 3rd Edition.

2. Kasai, K, J. A. Munshi, M. Lai, and F. Maison, "Viscoelastic Damper Hysteretic Model: Theory, Experiment, and Application", *Proceedings, Seminar on Seismic Isolation, Passive Energy Dissipation, and Active Control*, San Francisco, California, March 1993.

3. Becker, R. A., J. M. Chambers, and A. R. Wilks, "The New S Language. A Programming Environment for Data Analysis and Graphics", Wadsworth & Brooks/Cole Advanced Books and Software, Pacific Grove, California, 1988.

Table 2. Measured Peak Values & Temperature Increase

Test ID	Peak Displ. (inches)		Peak Load (kips)			Initial Temp. (°C)		Temp. Increase (°C)		
	D1	D2	D1	D2	Δ%	D1	D2	D1	D2	Δ%
eq02	0.22	0.22	32.4	32.5	NL	21.6	21.8	0.8	0.9	NL
eq08	0.76	0.75	70.6	73.0	3	22.1	22.1	5.0	5.9	18
eq10	0.95	0.95	70.2	74.0	5	23.6	23.3	5.9	7.1	20
h301	0.09	0.09	13.0	13.3	2	24.0	24.0	0.4	0.3	NL
h301a	0.10	0.09	11.6	13.2	14	24.5	24.5	0.4	0.4	0
h302	0.19	0.19	25.8	27.4	6	24.0	23.8	0.7	0.7	0
h305	0.47	0.47	57.1	60.8	6	24.1	23.7	2.6	3.0	15
h308	0.75	0.75	77.5	87.0	12	24.4	23.7	5.0	6.3	26
h1010	0.94	0.94	93.3	101.2	8	24.5	24.6	12.3	16.7	36

NL: difference between measurements is within instrumentation Noise Level.

Table 3. Estimated Values for shear moduli & loss factor

Test ID	G' (psi)			G" (psi)			η		
	D1	D2	Δ%	D1	D2	Δ%	D1	D2	Δ%
h301	290	310	7	390	400	3	1.4	1.3	-7
h301a	260	300	15	350	400	14	1.4	1.3	-7
h302	270	300	11	390	410	5	1.4	1.4	0
h305	230	250	9	350	380	9	1.5	1.5	0
h308	200	240	20	300	320	7	1.5	1.4	-6
h1010	180	170	-5	240	260	8	1.4	1.6	14

Table 4. Estimated Mechanical Properties versus Values on Polymer 109 Database

Test ID	G' (psi)			G" (psi)			η		
	Database	Estimated	Δ%	Database	Estimated	Δ%	Database	Estimated	Δ%
h301	291*	300	3	385*	395	3	1.33*	1.35	2
h302	257	285	11	359	400	11	1.40	1.40	0
h305	201	240	19	296	365	23	1.47	1.50	2
h308	165	220	33	243	310	28	1.47	1.45	-1
h1010	140	175	25	209	250	20	1.49	1.5	1

* Database value is for 5% shear strain. Estimated value is for 10% shear strain.

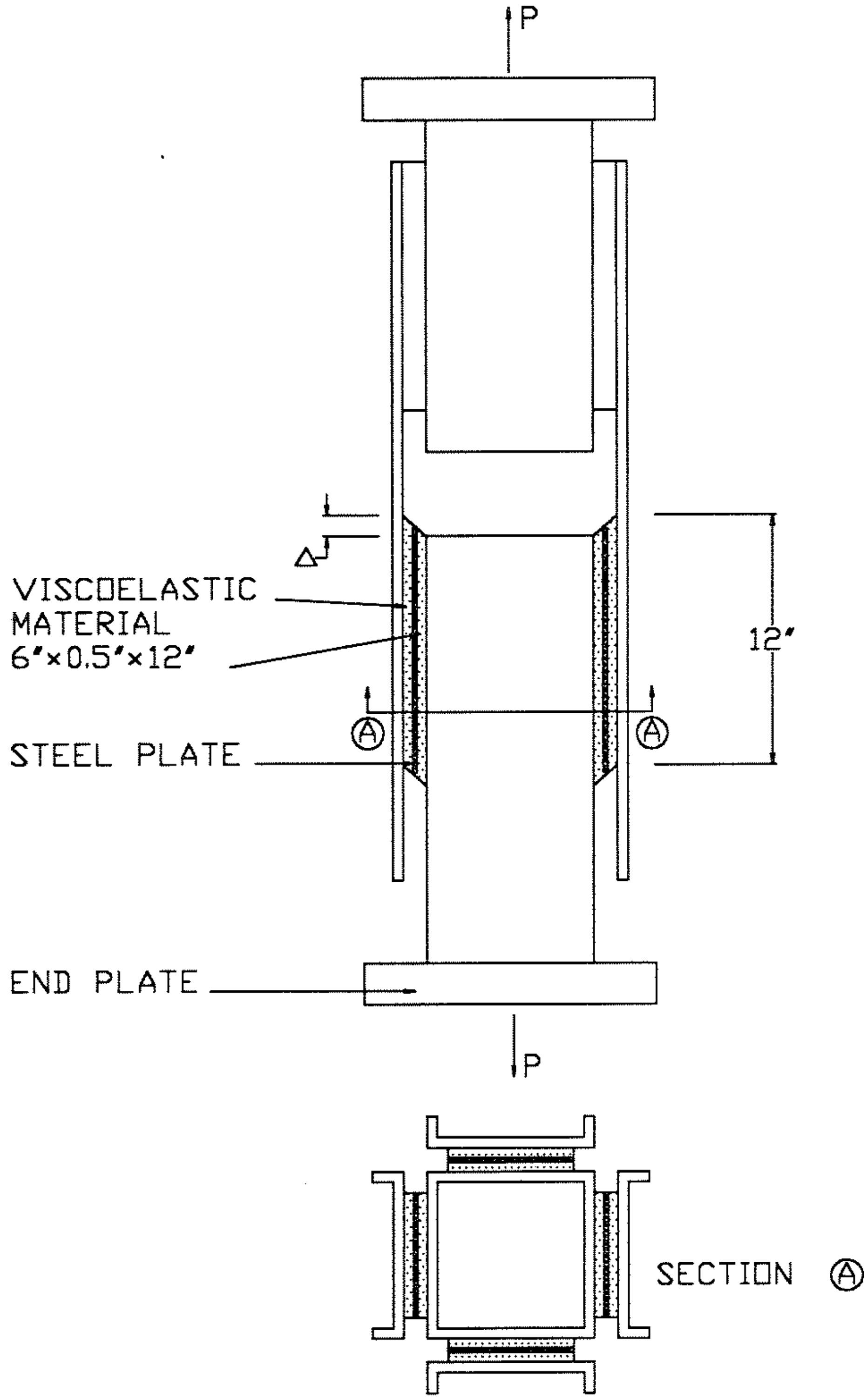


Figure 1. **VE damper schematics.**

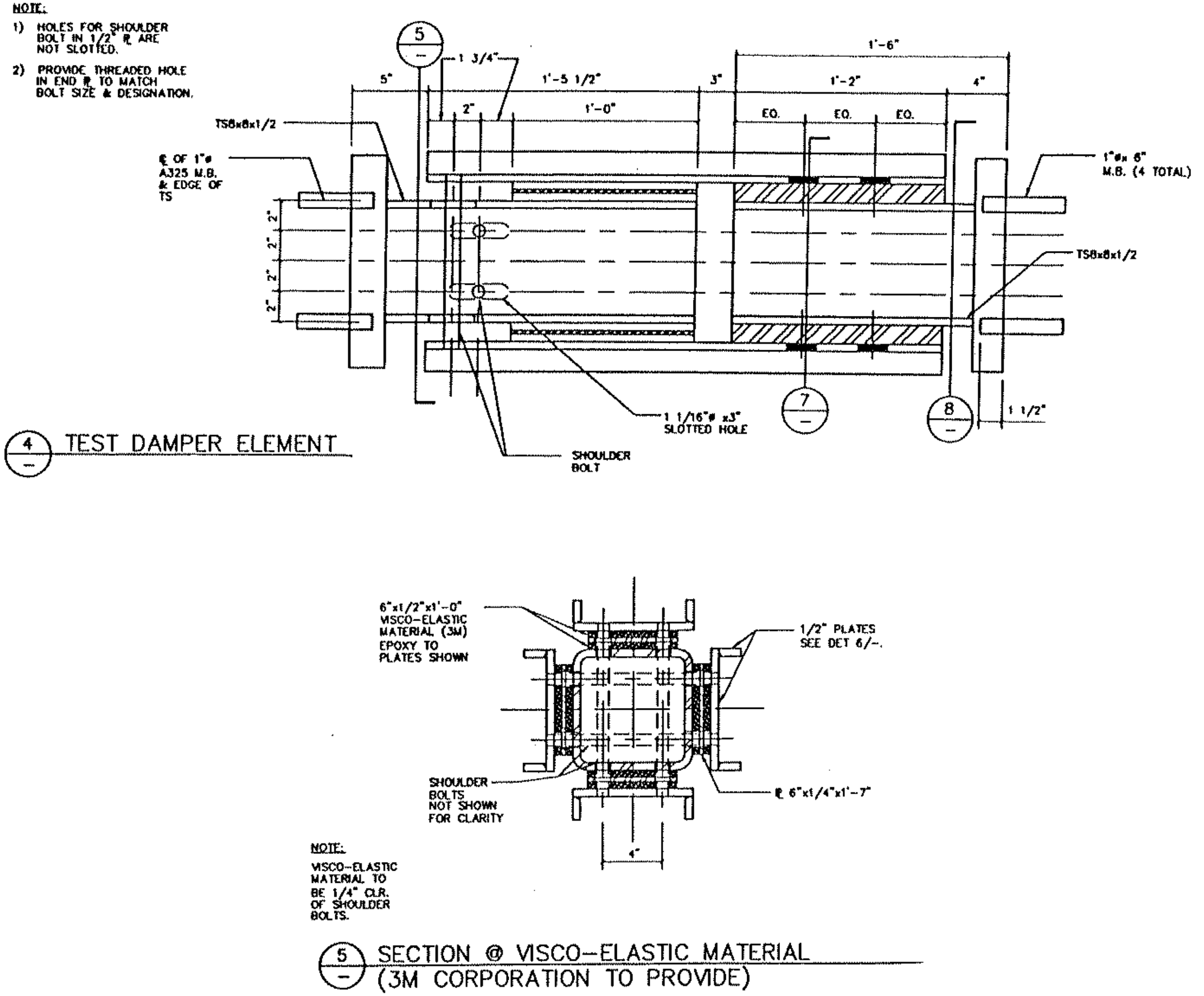


Figure 2. VE damper construction drawings (partial).

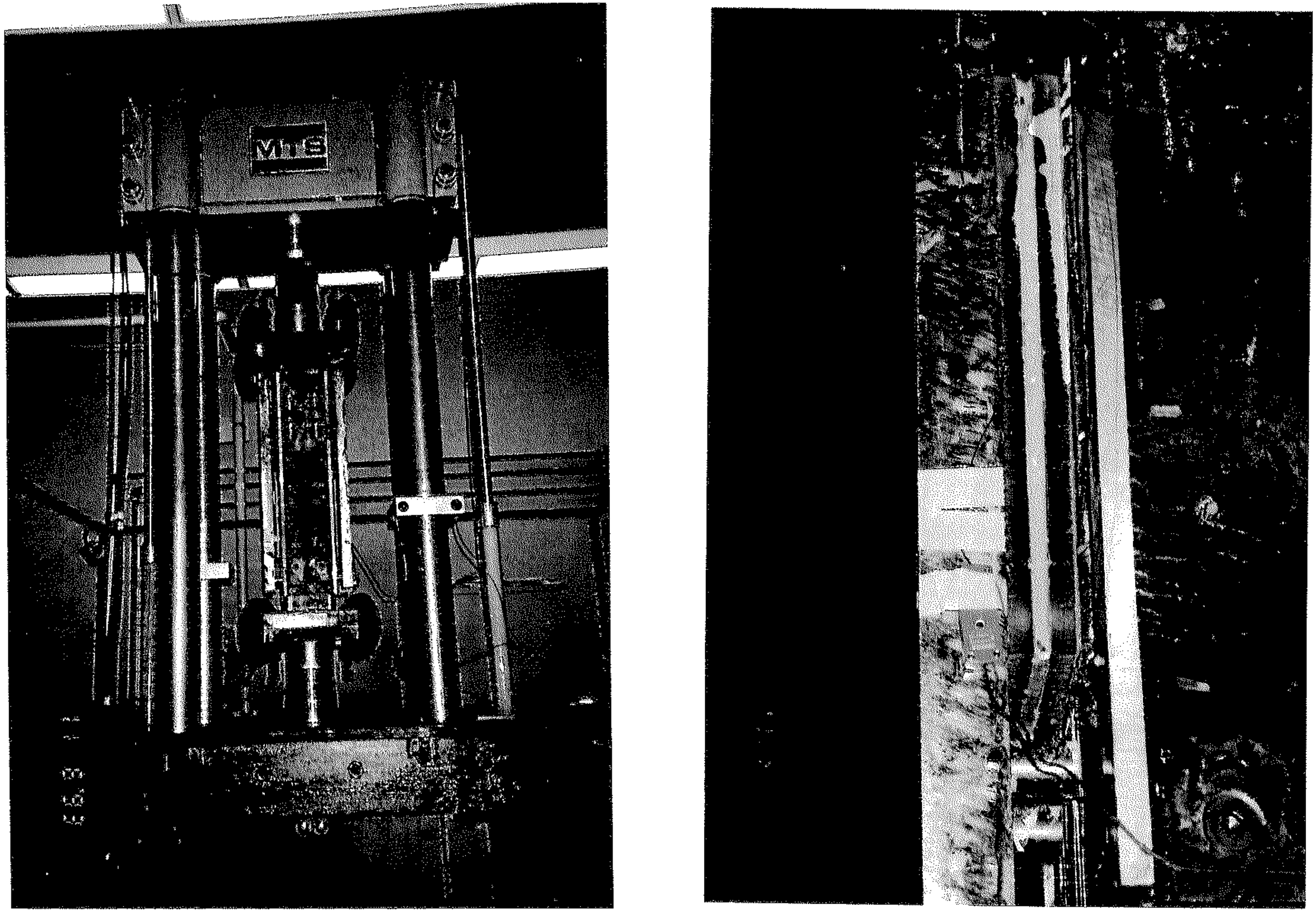


Figure 3. Test setup & closeup of VE material.

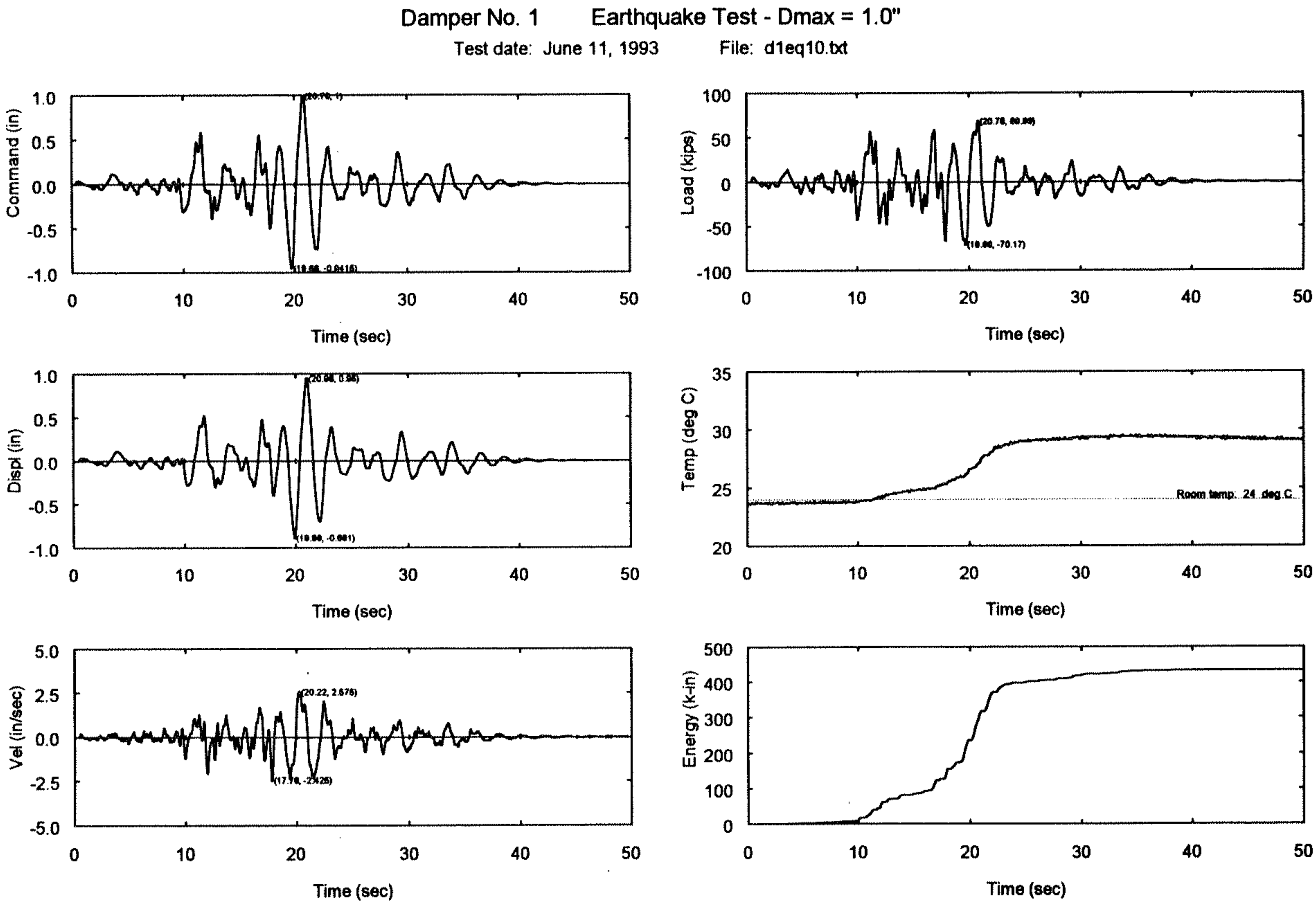


Figure 4a1. Maximum Credible Earthquake test results. Damper # 1.

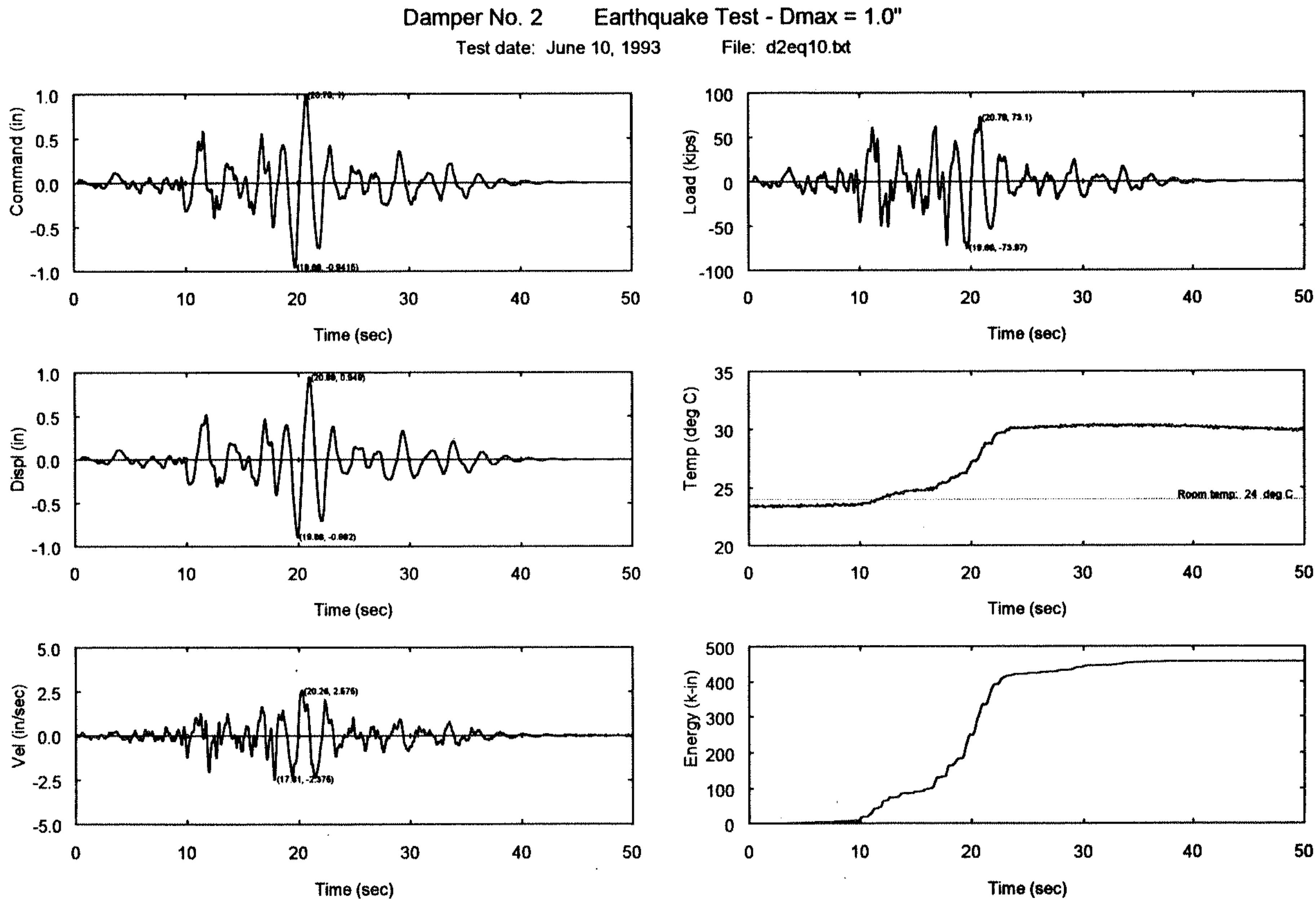


Figure 4a2. Maximum Credible Earthquake test results. Damper # 2.

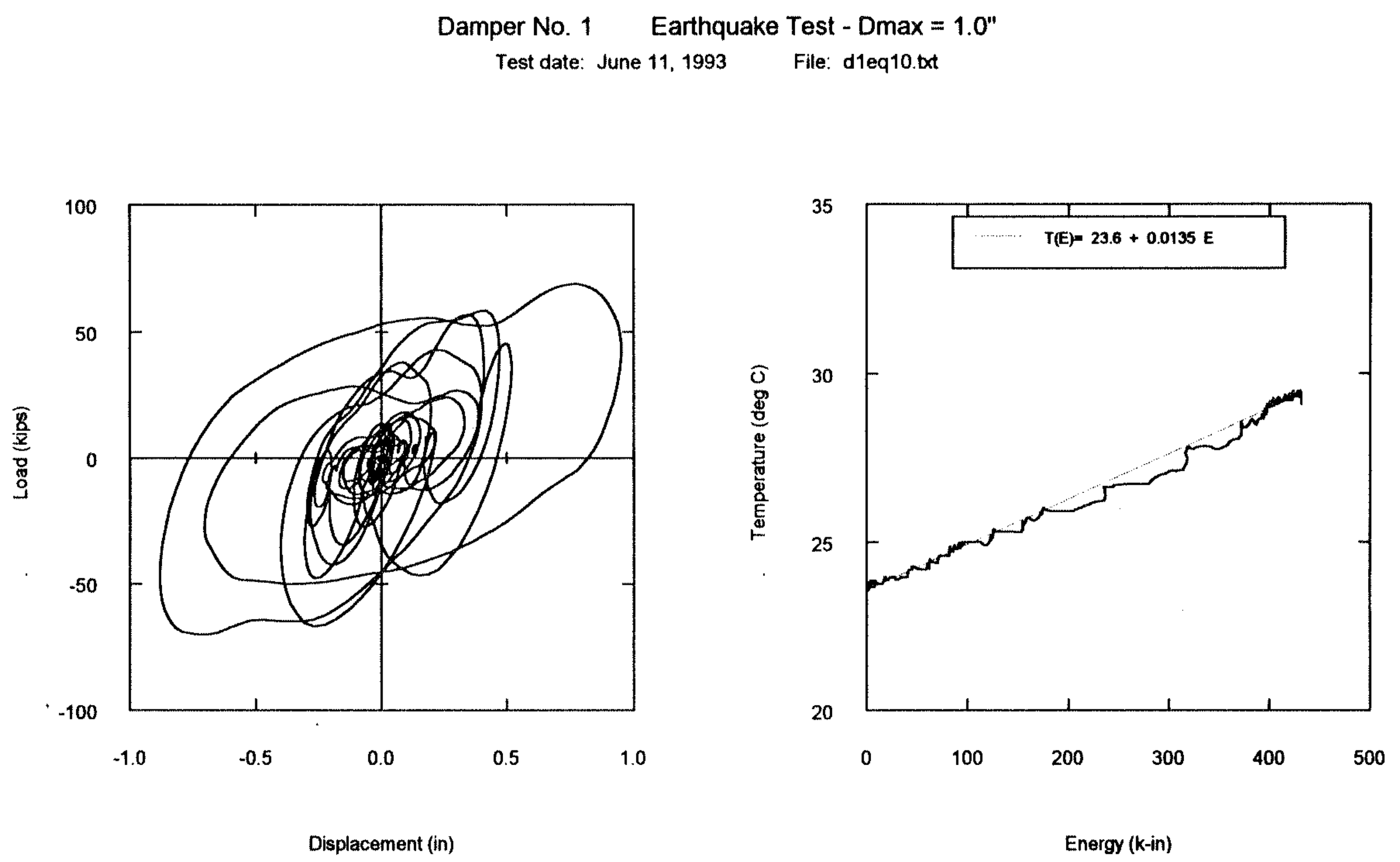


Figure 4b1. Maximum Credible Earthquake test results. Damper # 1.

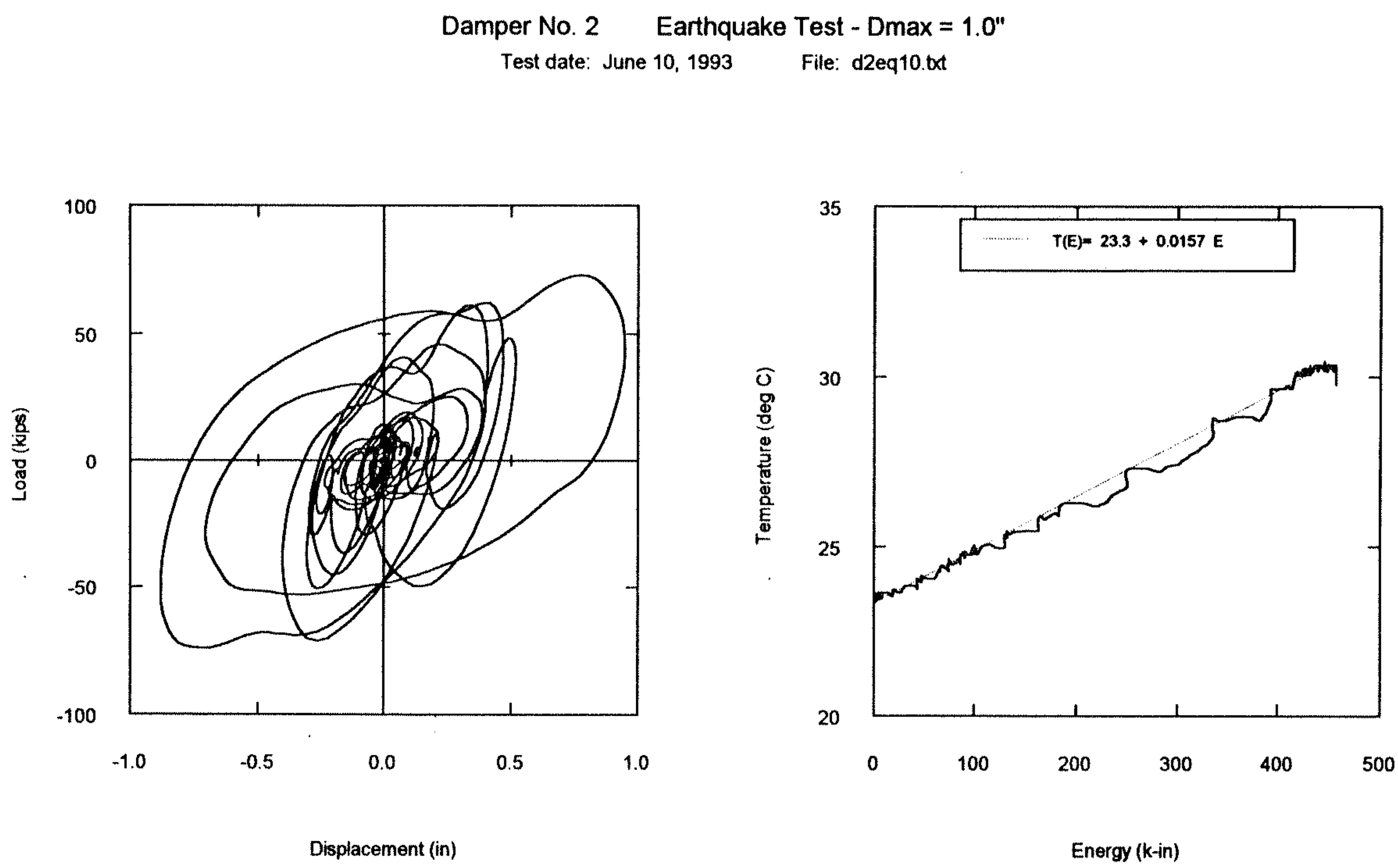


Figure 4b2. Maximum Credible Earthquake test results. Damper # 2.

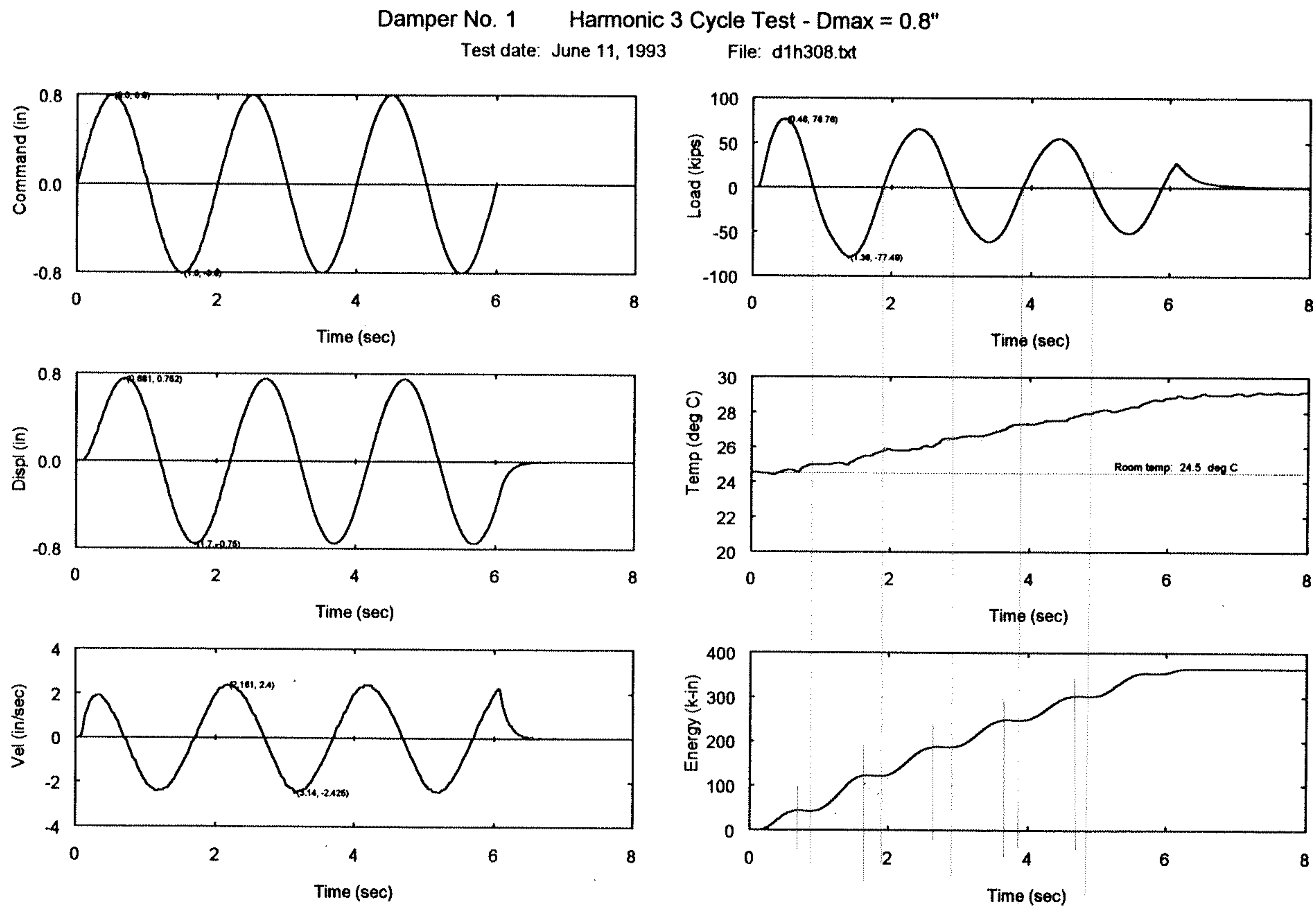


Figure 5a1. 3-cycle 80% shear strain test results. Damper # 1.

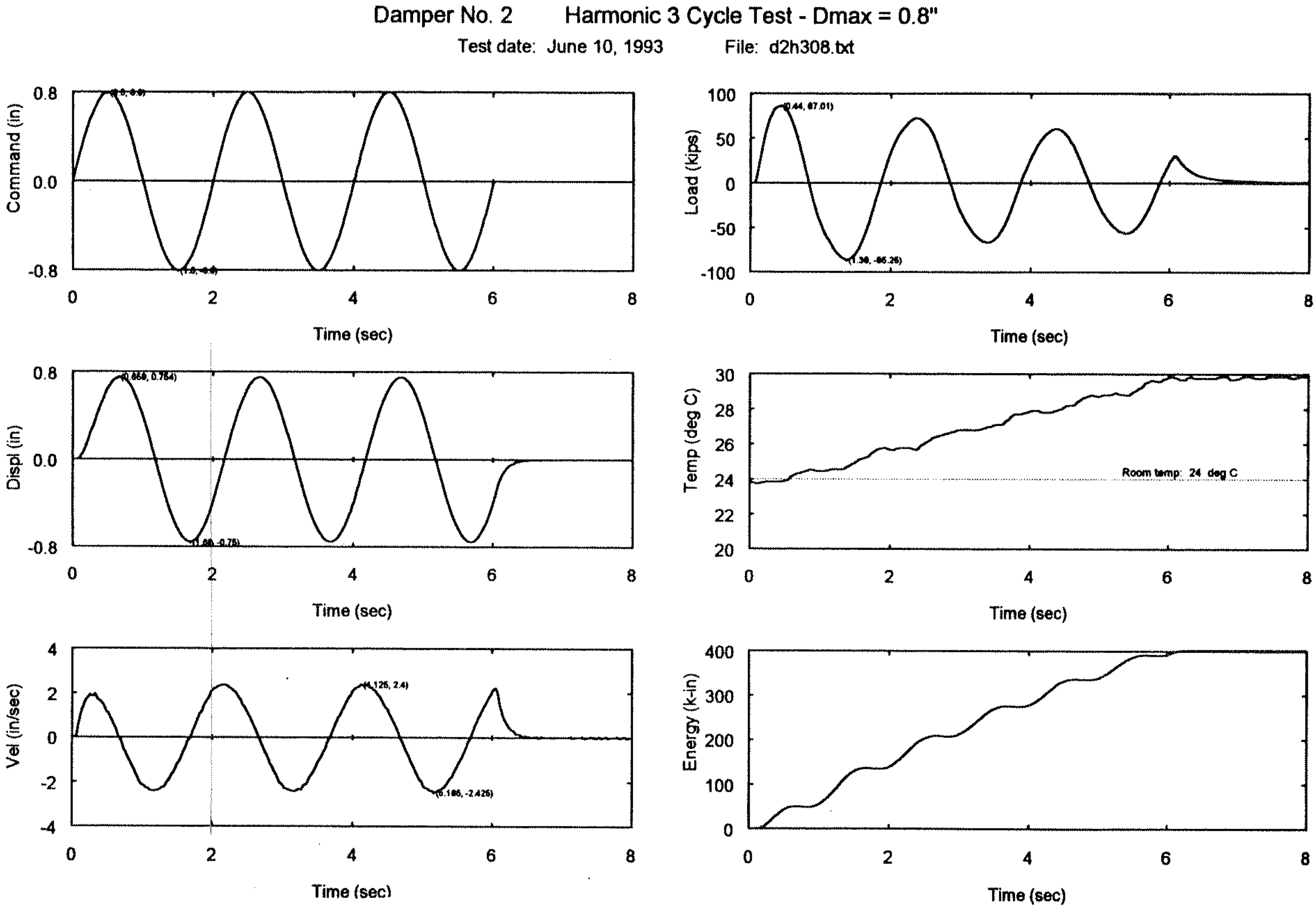


Figure 5a2. 3-cycle 80% shear strain test results. Damper # 2.

Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.8"

Test date: June 11, 1993 File: d1h308.txt

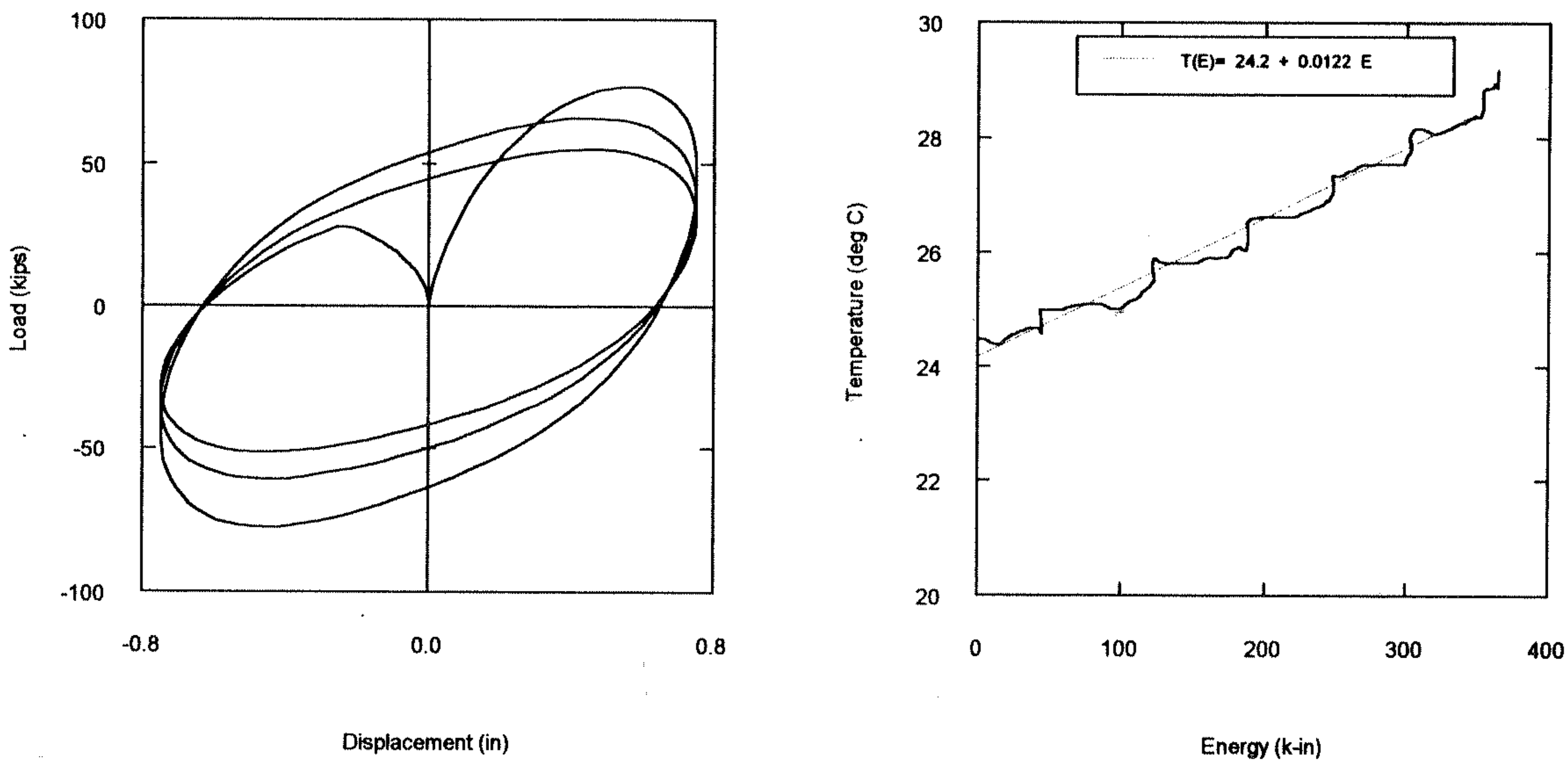


Figure 5b1. 3-cycle 80% shear strain test results. Damper # 1.

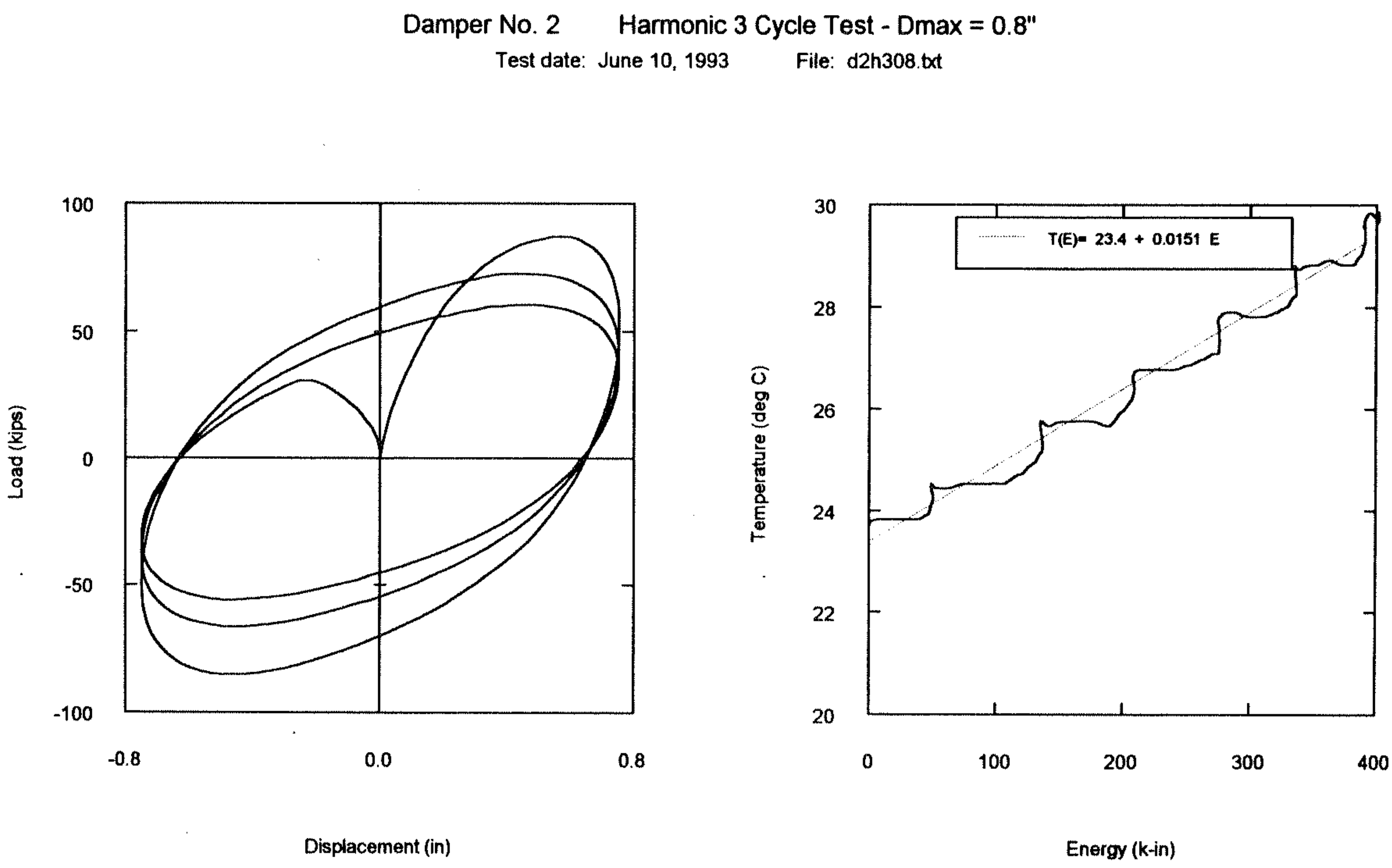


Figure 5b2. 3-cycle 80% shear strain test results. Damper # 2.

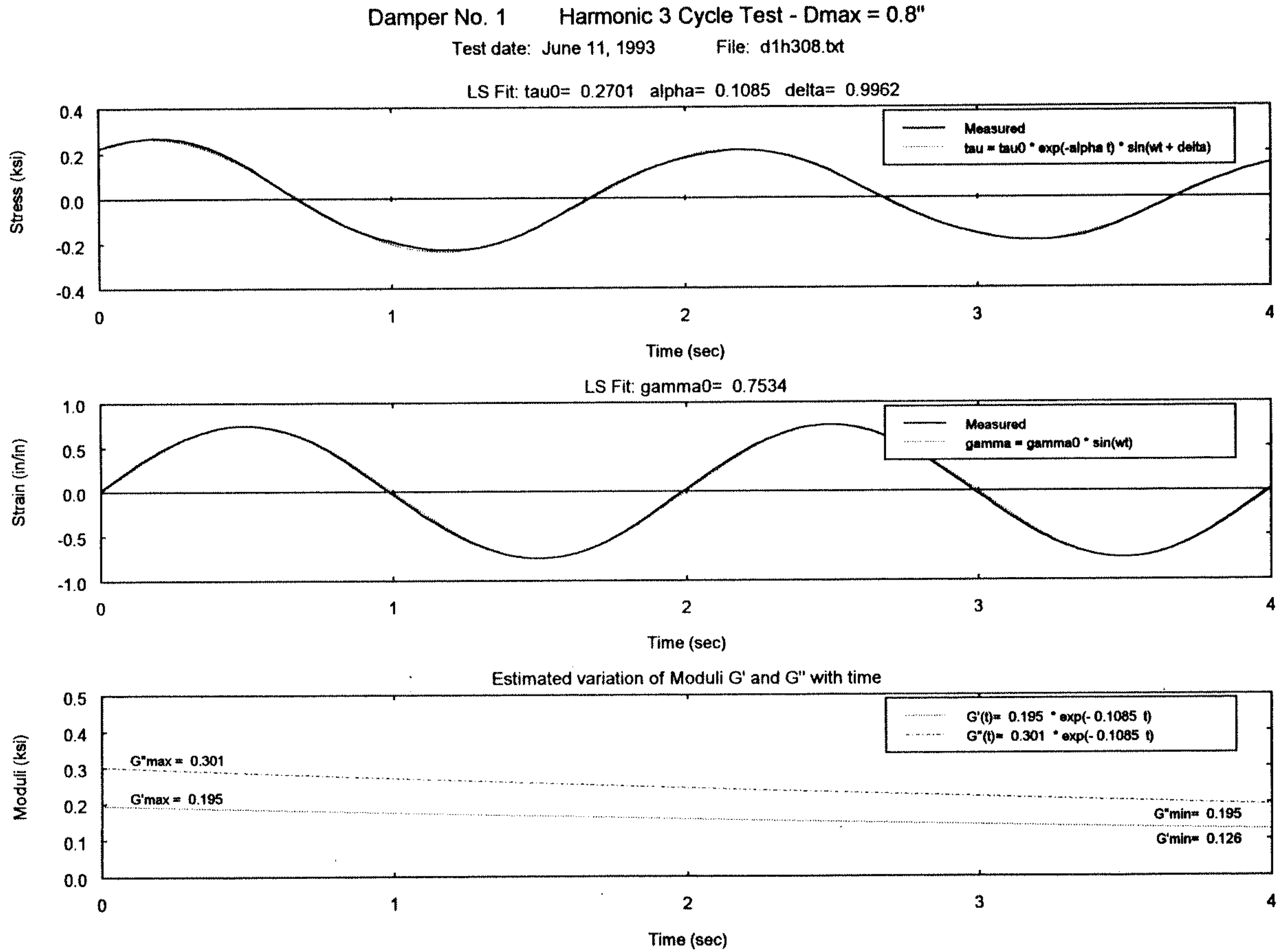


Figure 5c1. **3-cycle 80% shear strain test. Estimation of mechanical properties. Damper # 1.**

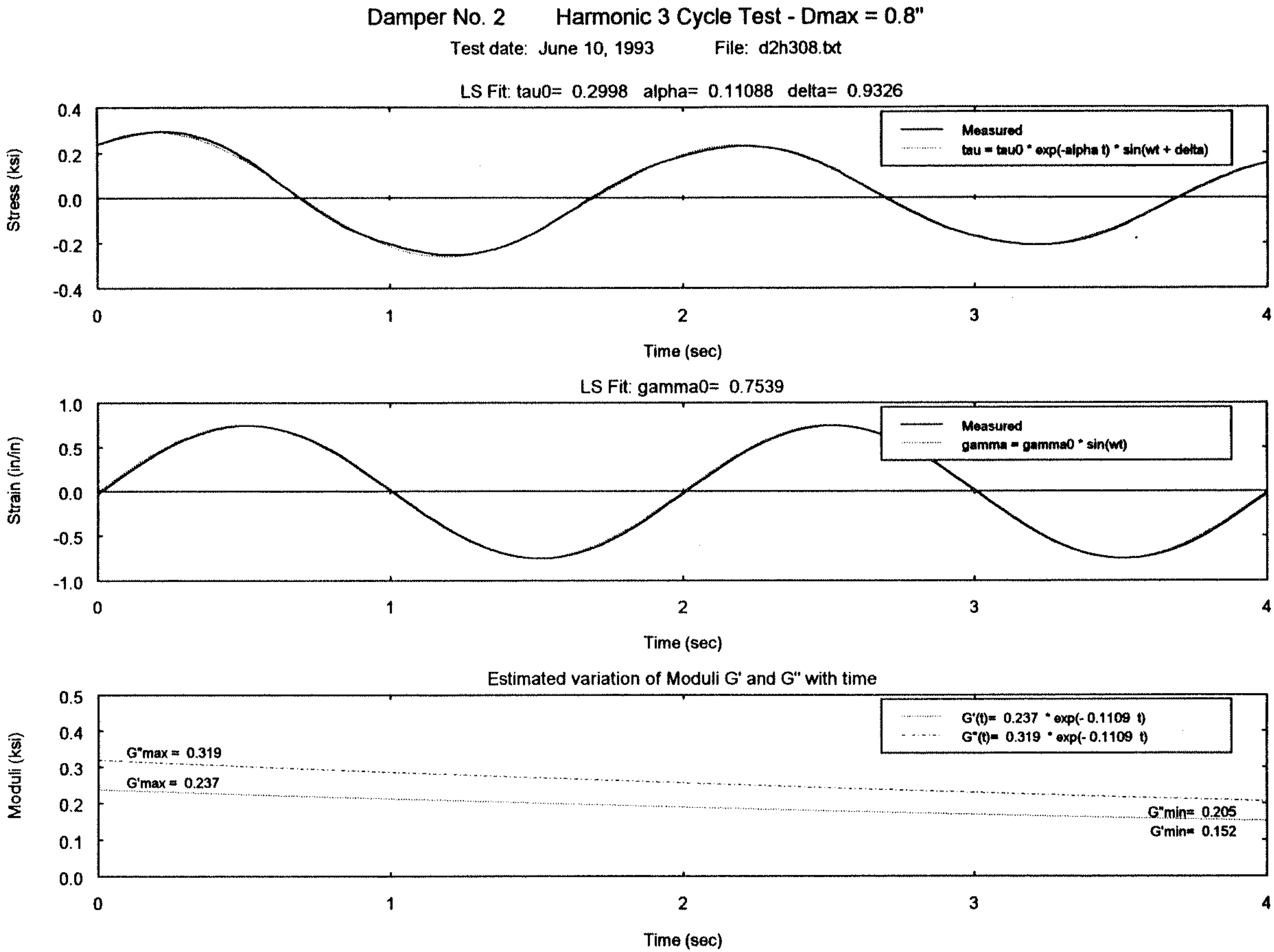
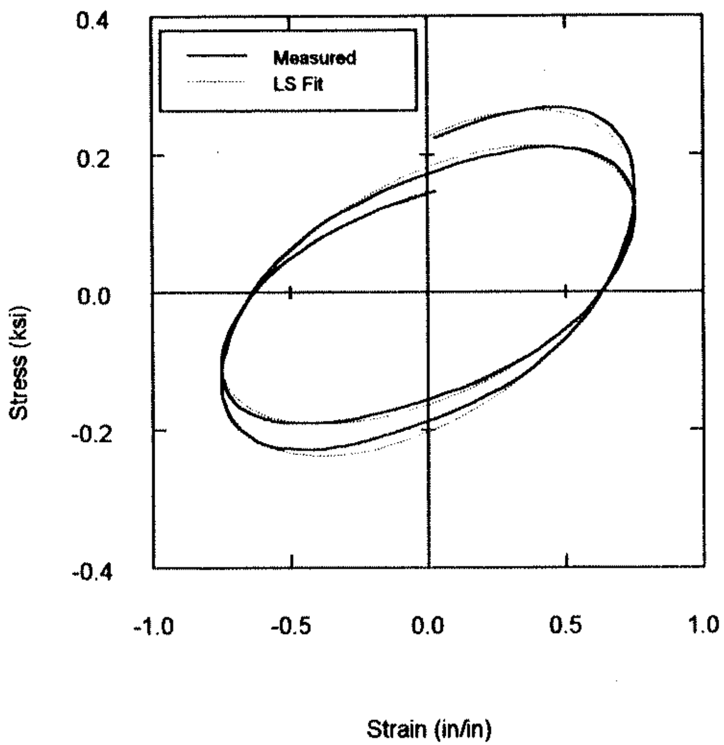


Figure 5c2. 3-cycle 80% shear strain test. Estimation of mechanical properties. Damper # 2.

Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.8"

Test date: June 11, 1993 File: d1h308.txt



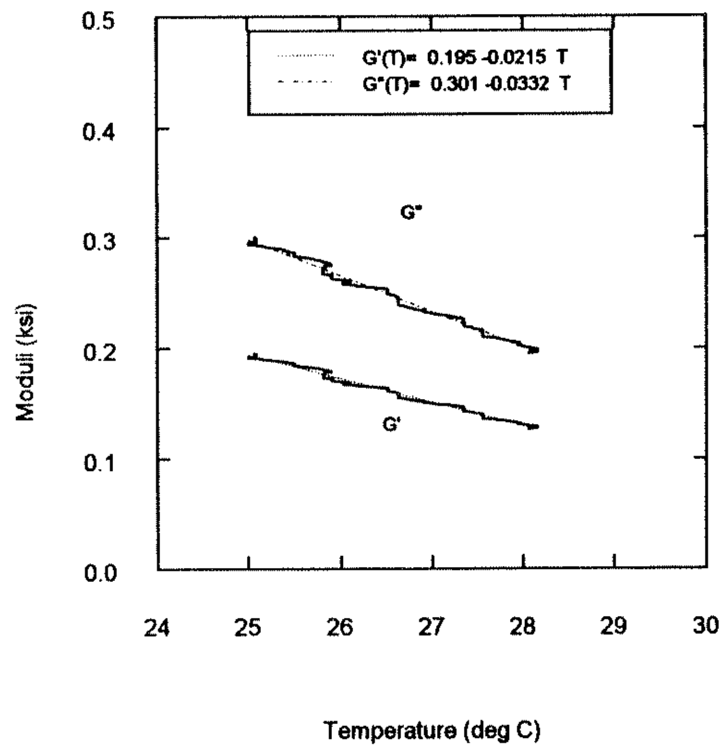
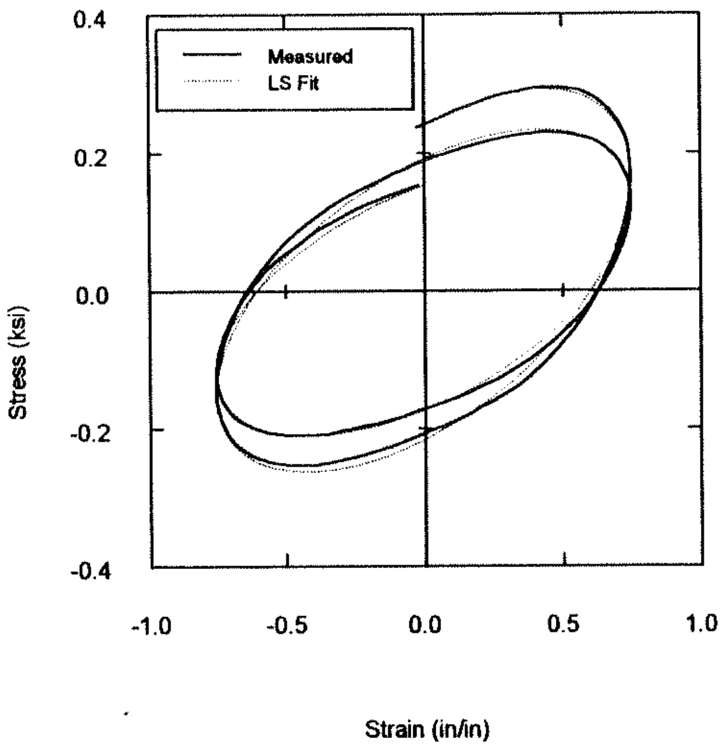


Figure 5d1. 3-cycle 80% shear strain test. Estimation of mechanical properties. Damper # 1.

Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.8"

Test date: June 10, 1993 File: d2h308.txt



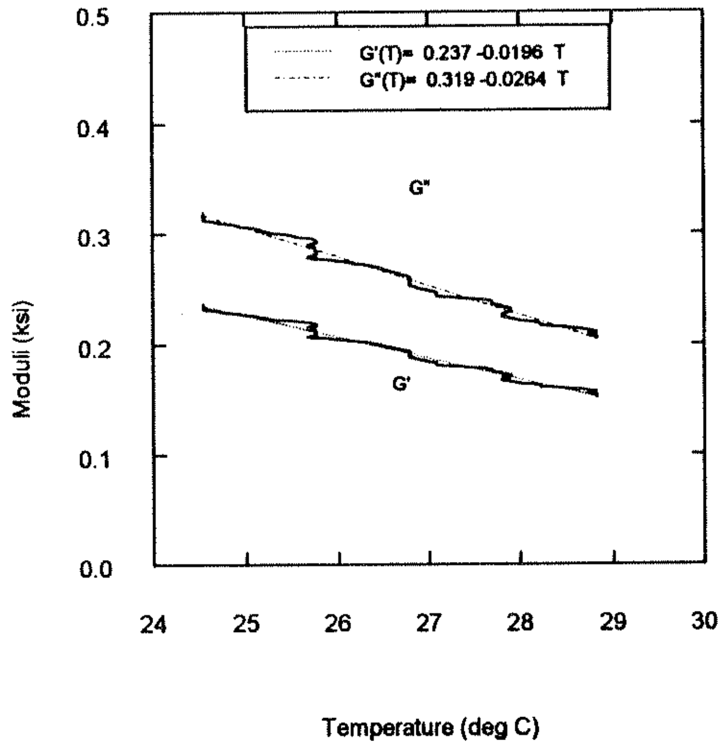


Figure 5d2. **3-cycle 80% shear strain test. Estimation of mechanical properties. Damper # 2.**

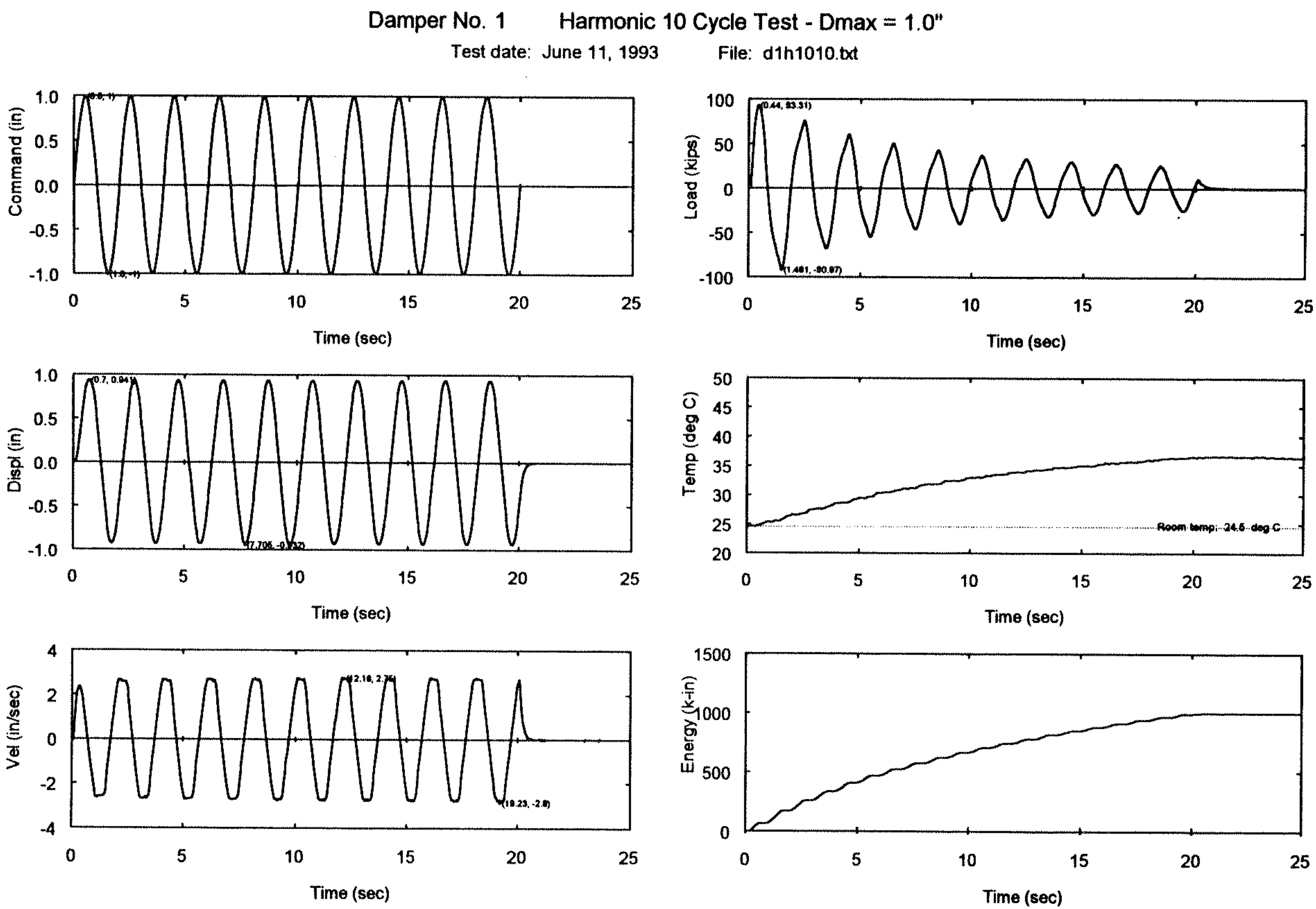


Figure 6a1. 10-cycle 100% shear strain test results. Damper # 1.

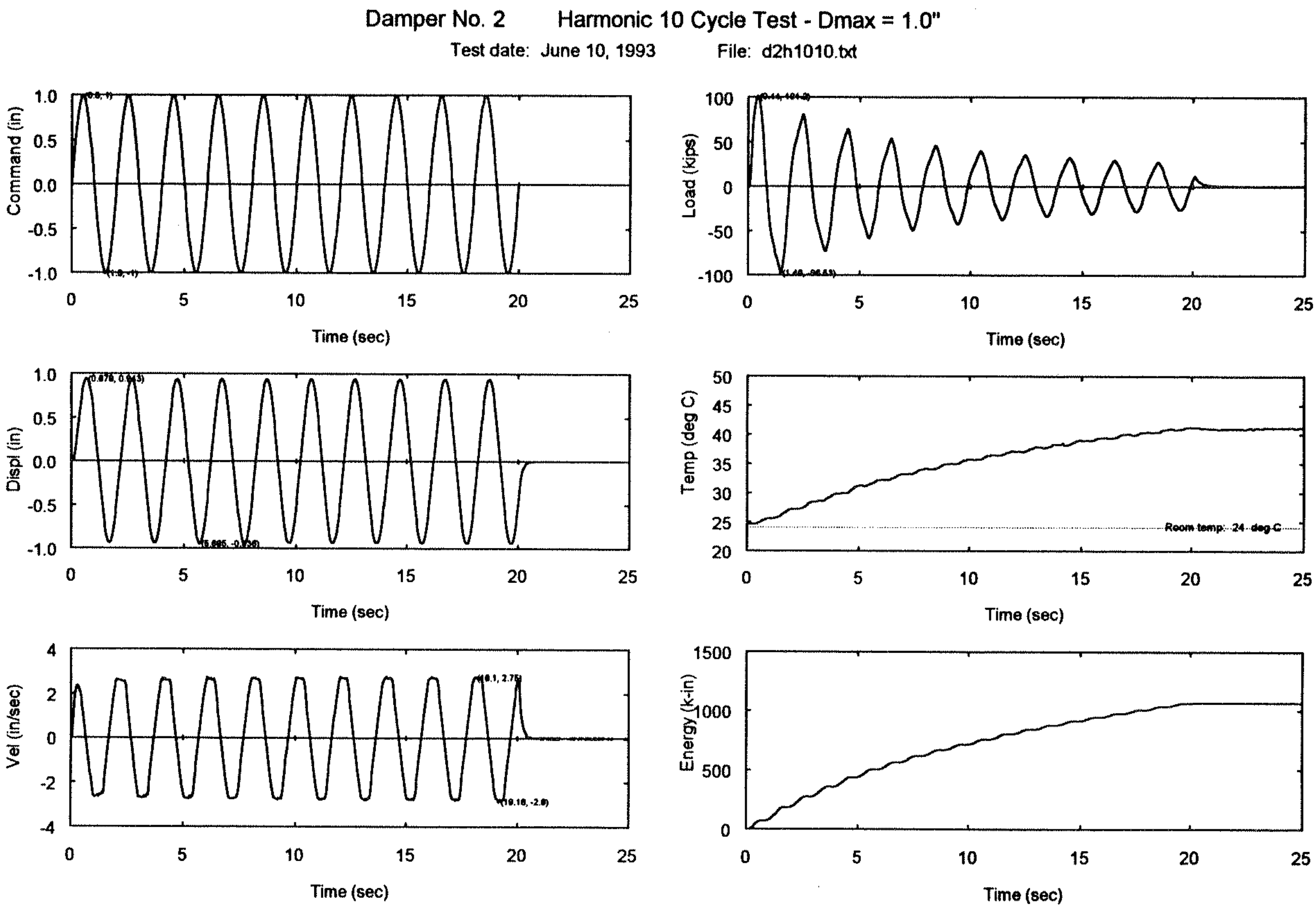
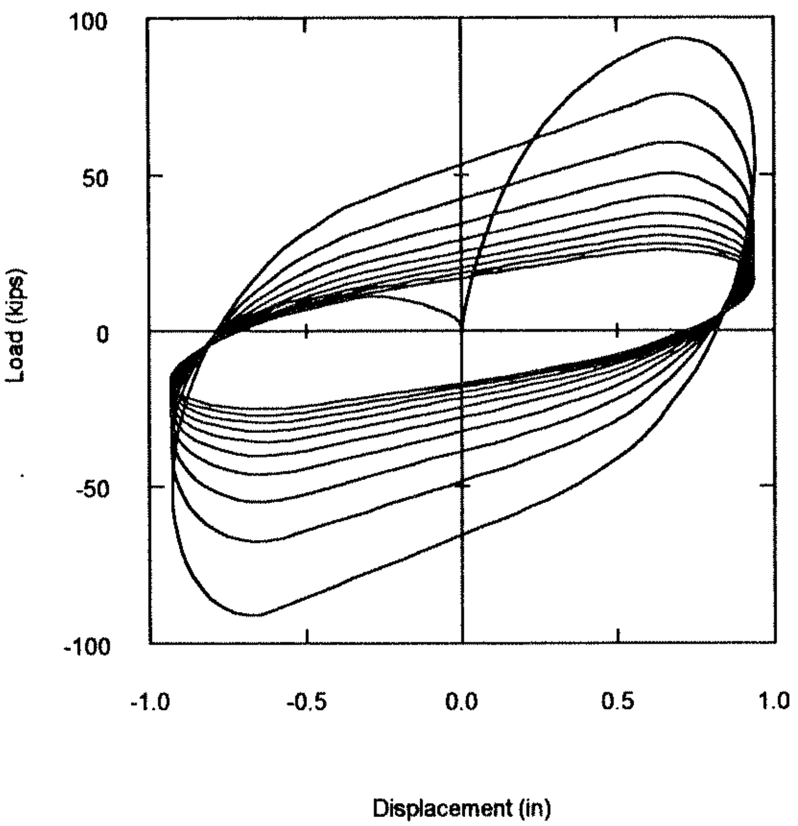


Figure 6a2. **10-cycle 100% shear strain test results. Damper # 2.**

Damper No. 1 Harmonic 10 Cycle Test - Dmax = 1.0"

Test date: June 11, 1993 File: d1h1010.txt



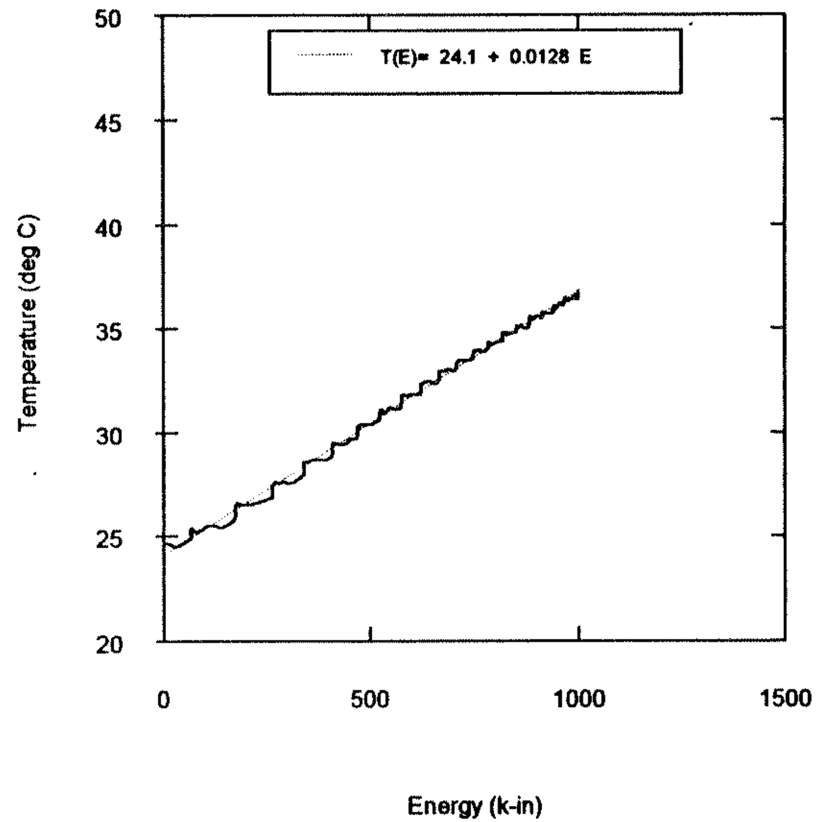


Figure 6b2. 10-cycle 100% shear strain test results. Damper # 2.

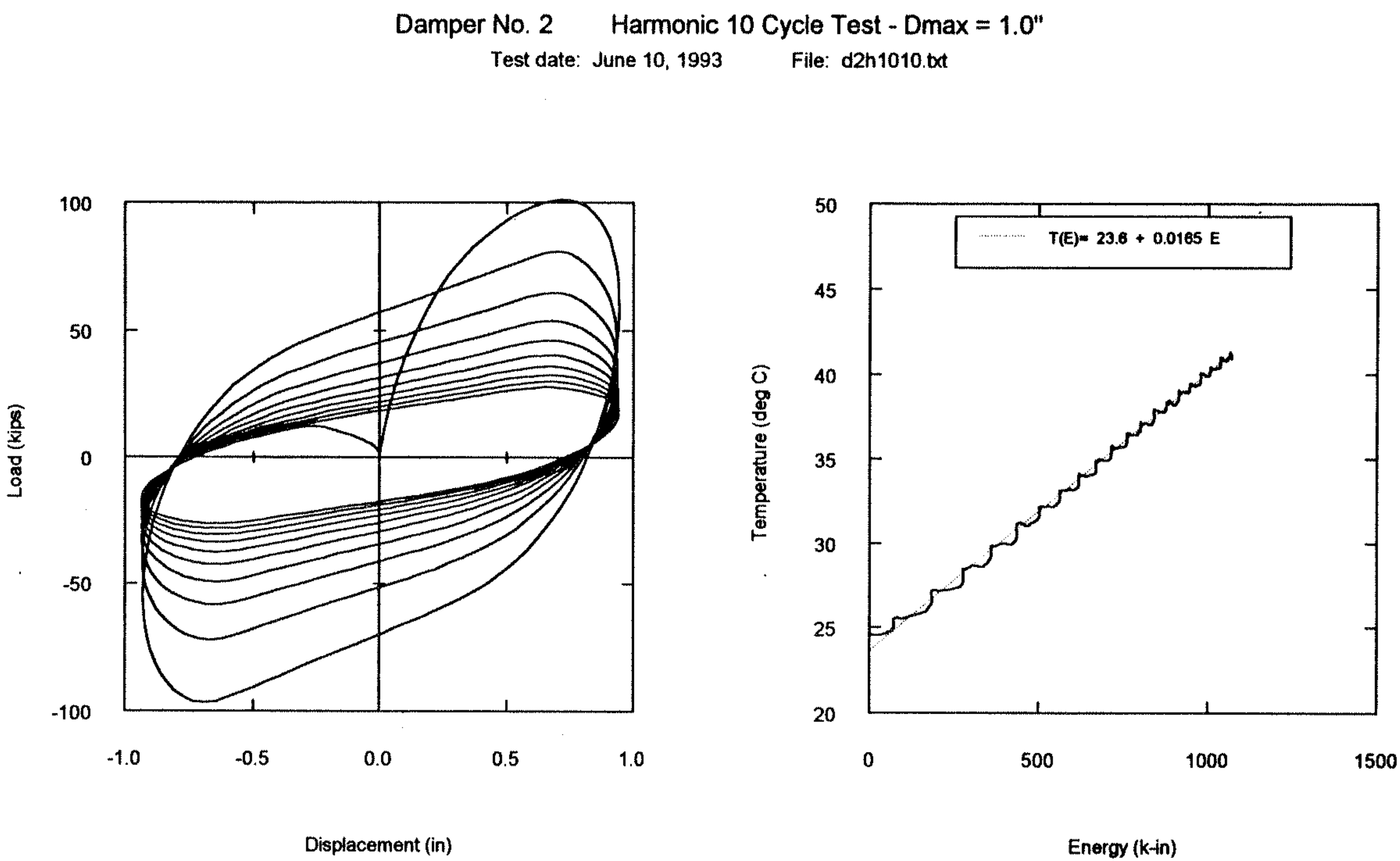


Figure 6b1. 10-cycle 100% shear strain test results. Damper # 1.

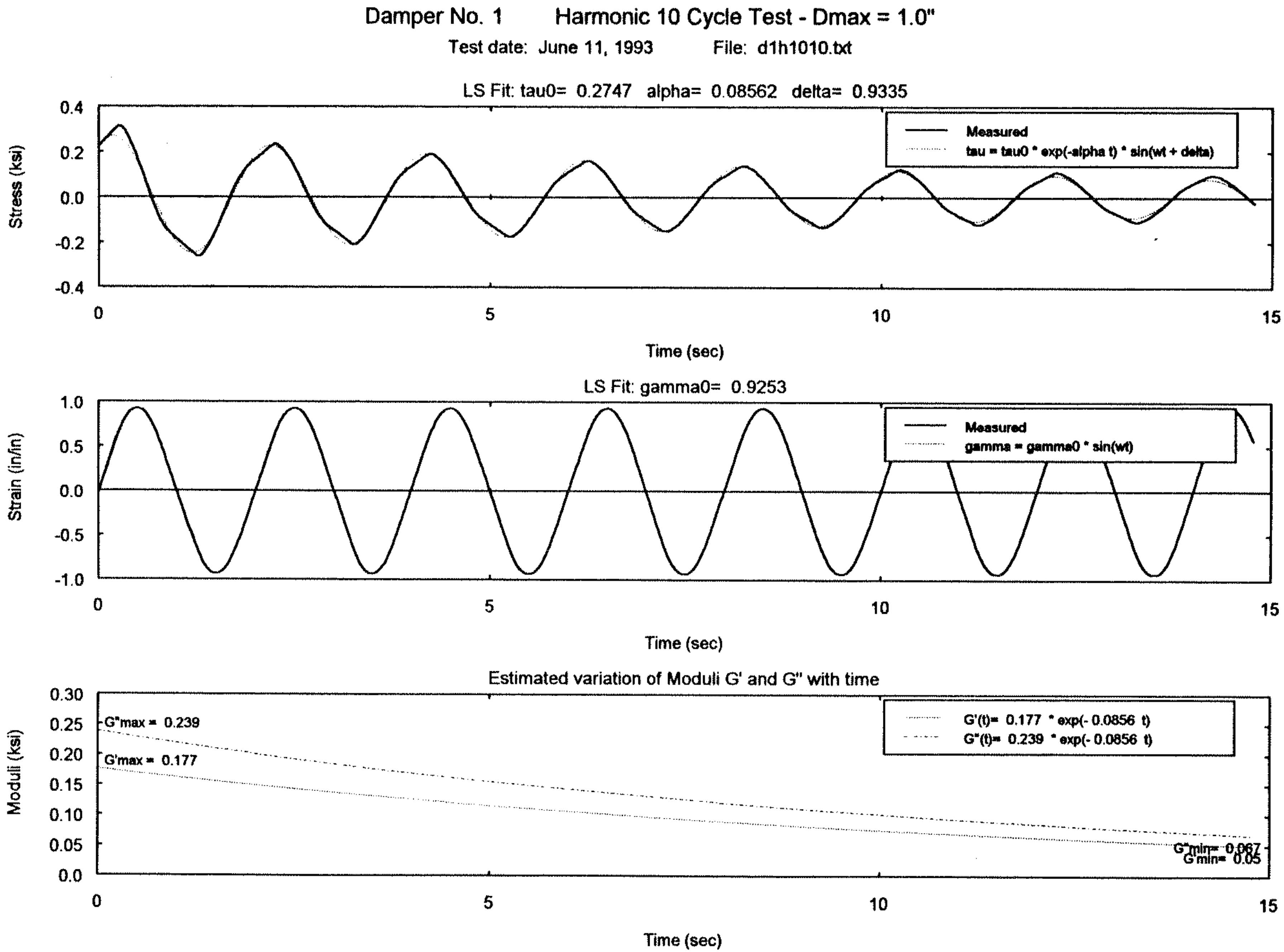


Figure 6c1. **10-cycle 100% shear strain test. Estimation of mechanical properties. Damper # 1.**

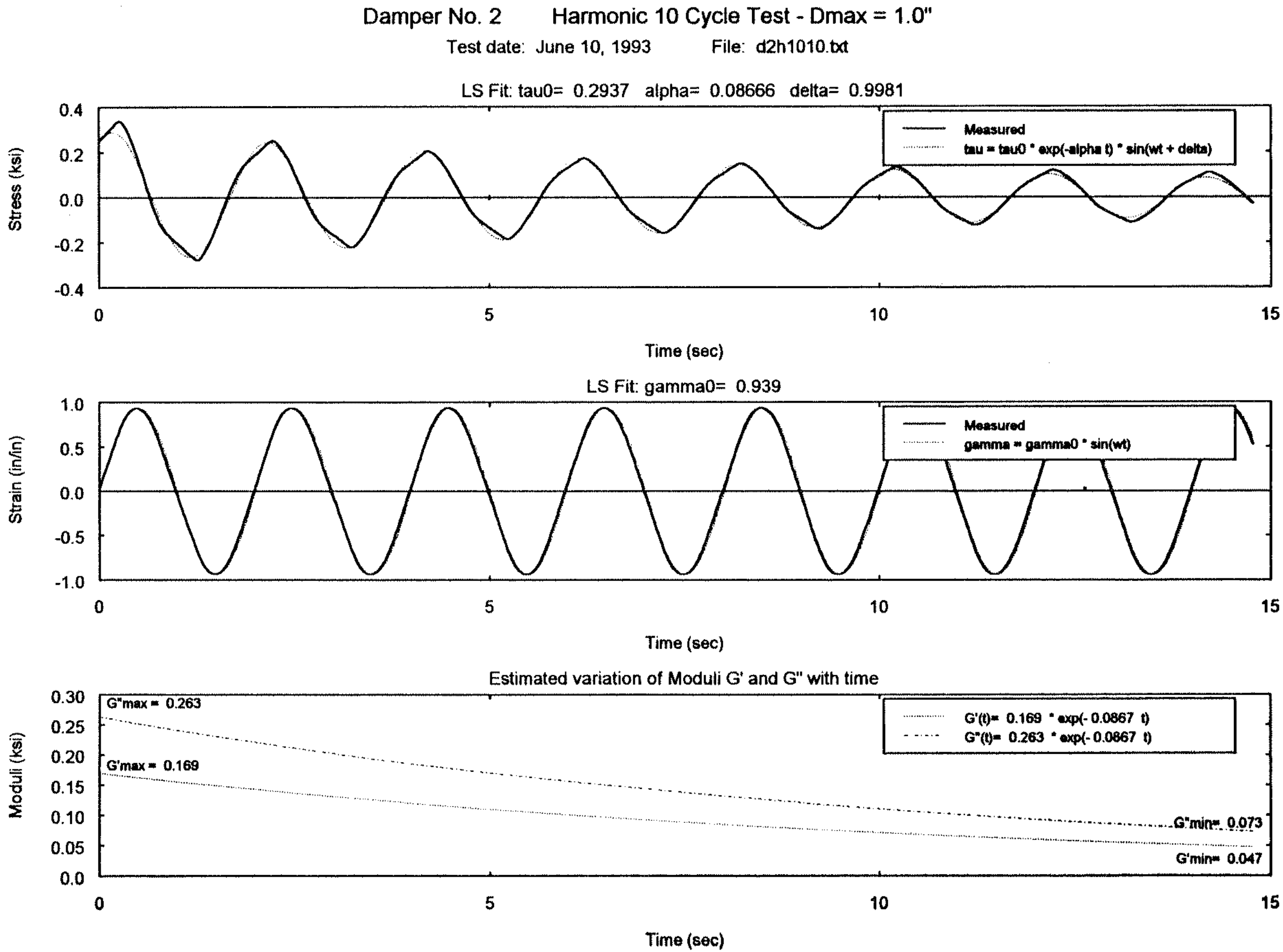
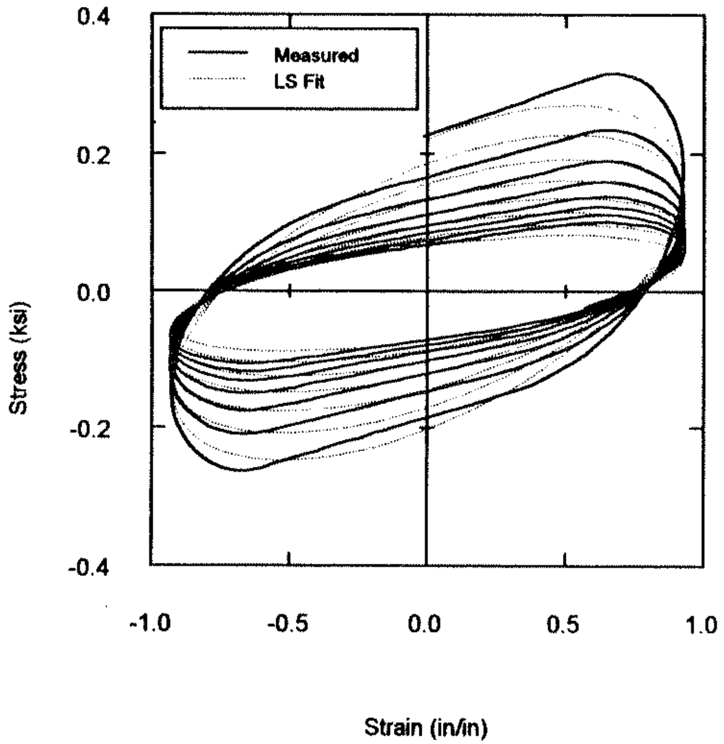


Figure 6c2. **10-cycle 100% shear strain test. Estimation of mechanical properties. Damper # 2.**

Damper No. 1 Harmonic 10 Cycle Test - Dmax = 1.0"

Test date: June 11, 1993 File: d1h1010.txt



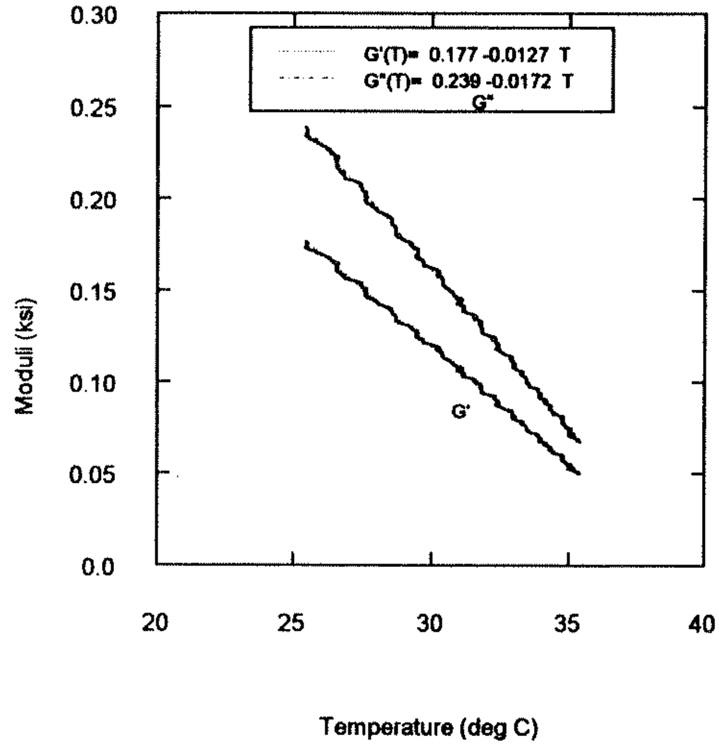


Figure 6d1. 10-cycle 100% shear strain test. Estimation of mechanical properties. Damper # 1.

Damper No. 2 Harmonic 10 Cycle Test - Dmax = 1.0"

Test date: June 10, 1993 File: d2h1010.txt

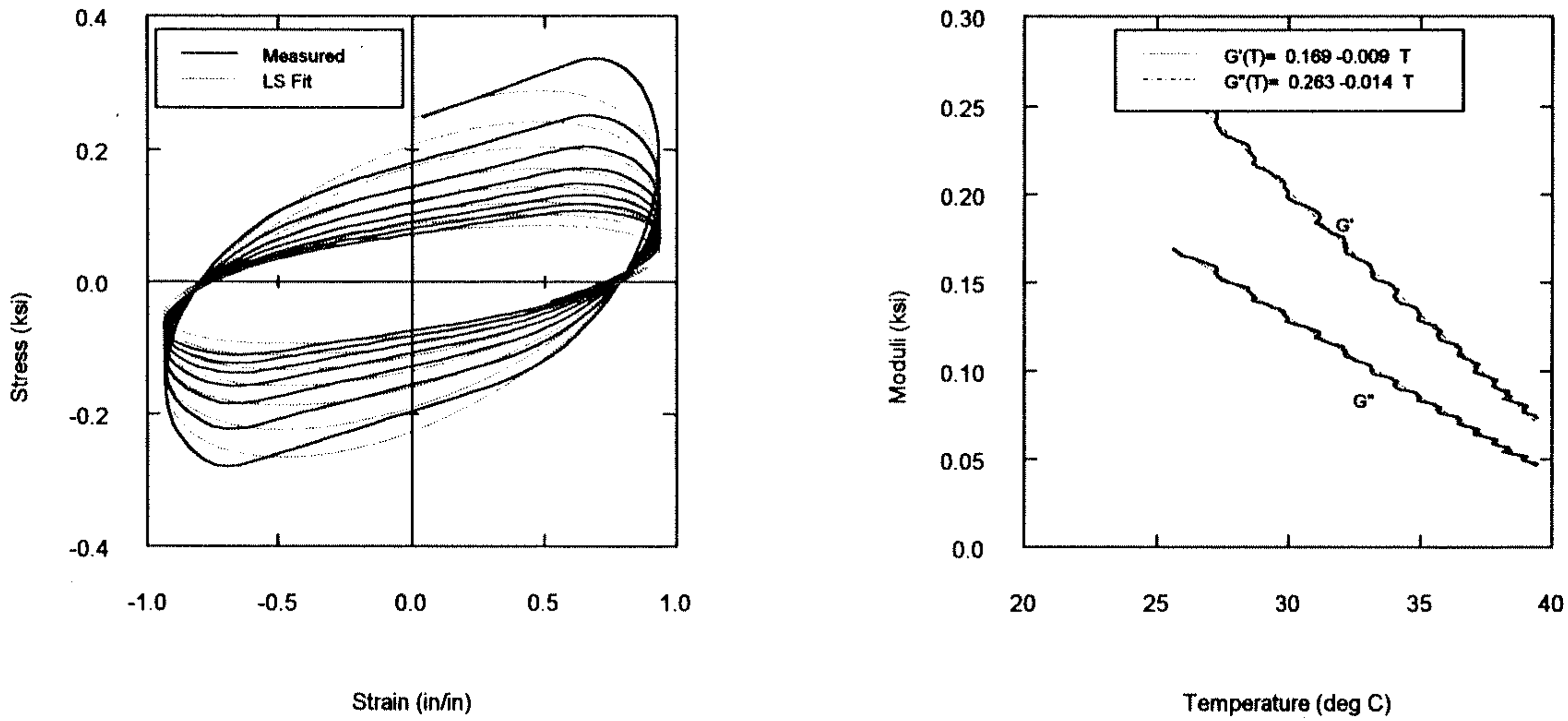


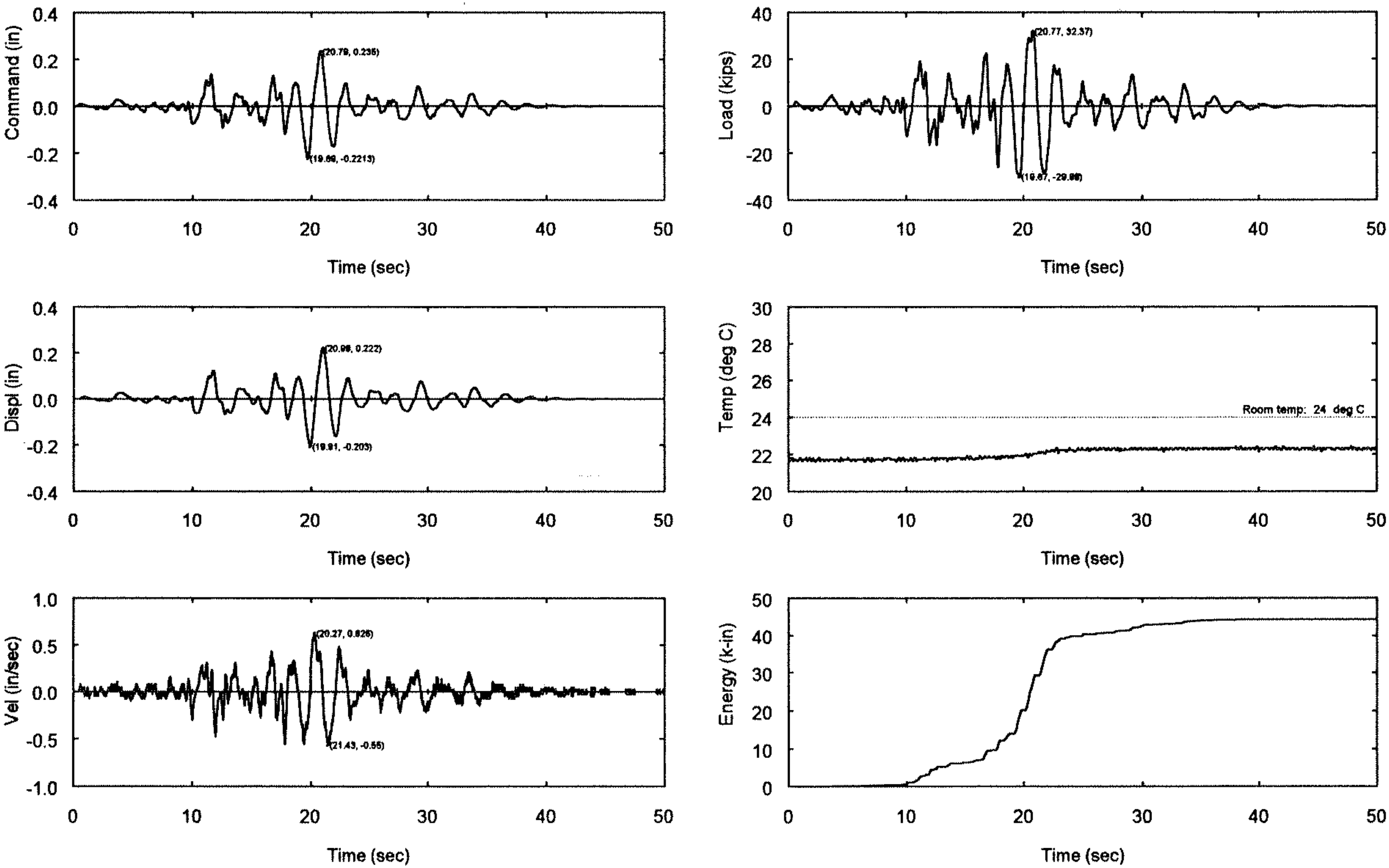
Figure 6d2. 10-cycle 100% shear strain test. Estimation of mechanical properties. Damper # 2.

APPENDIX A

PLOTS OF MEASURED & CALCULATED DATA

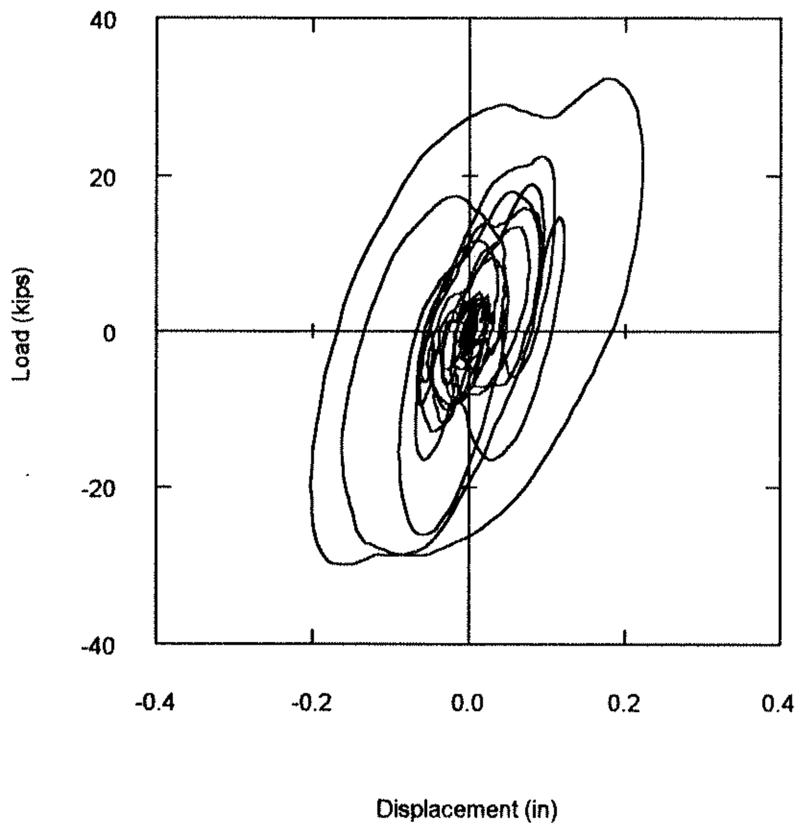
Damper No. 1 Earthquake Test - Dmax = 0.235"

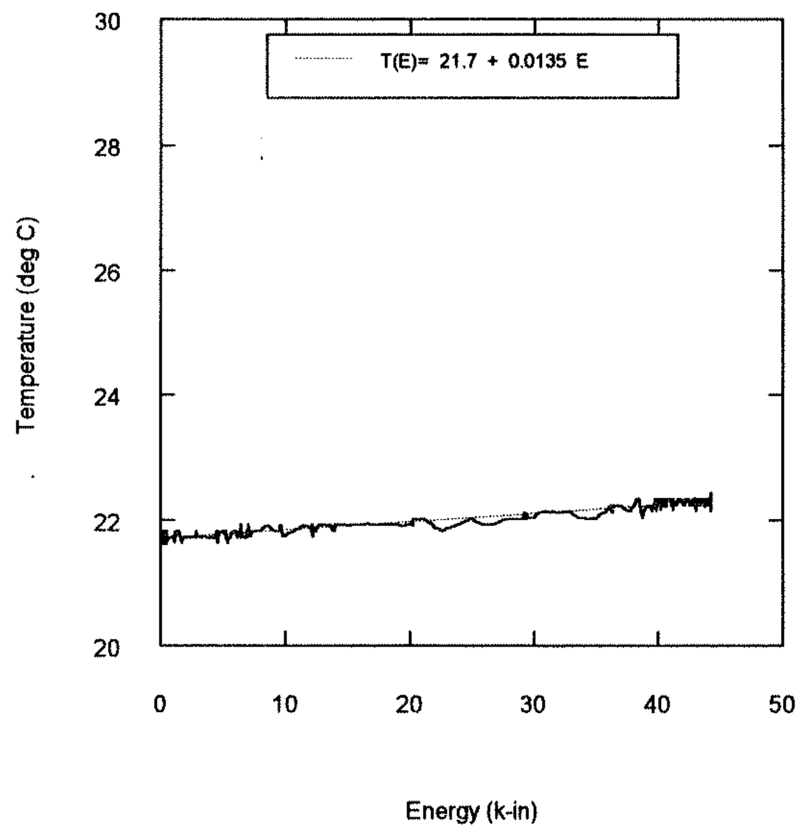
Test date: June 11, 1993 File: d1eq02.txt



Damper No. 1 Earthquake Test - Dmax = 0.235"

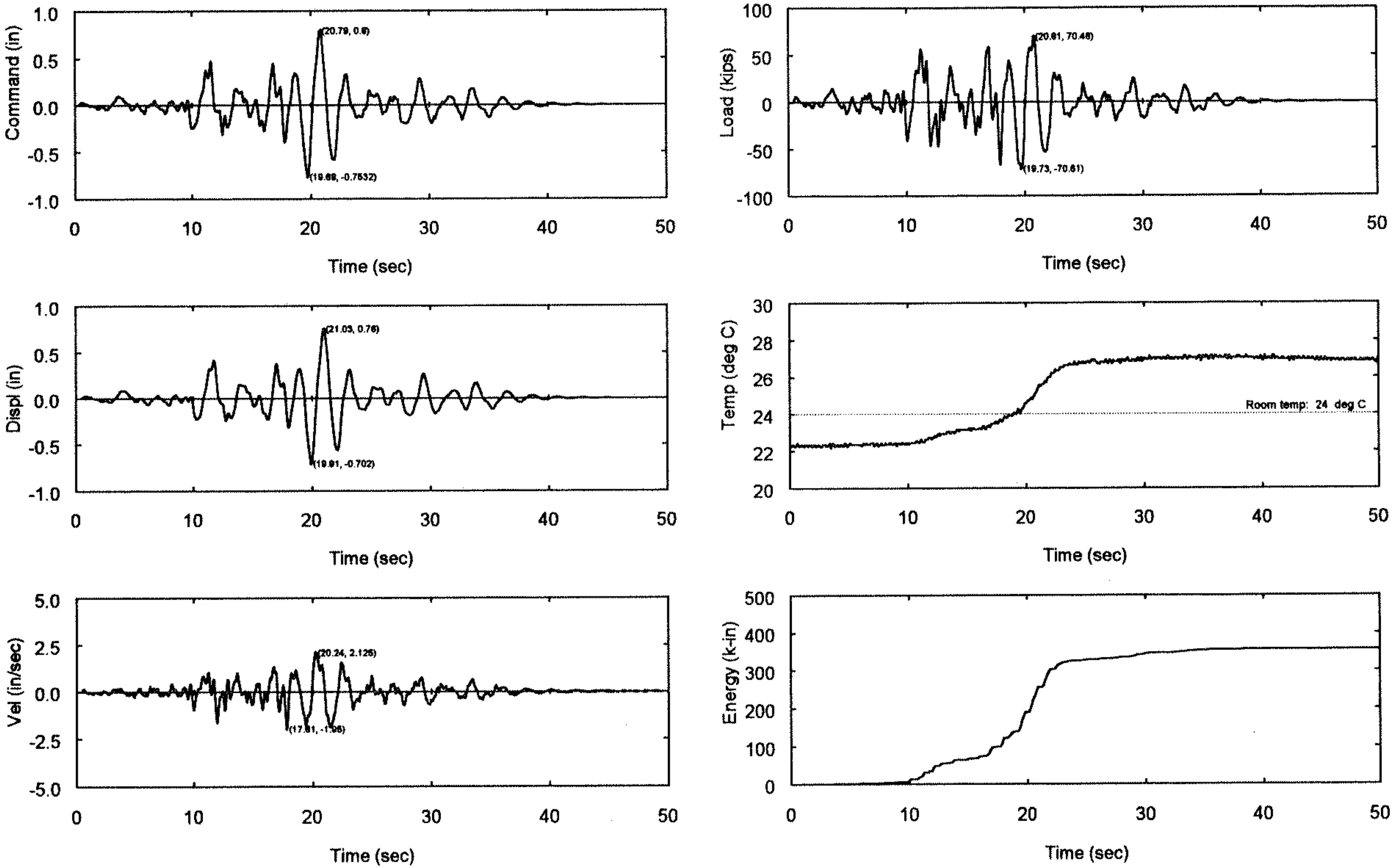
Test date: June 11, 1993 File: d1eq02.txt





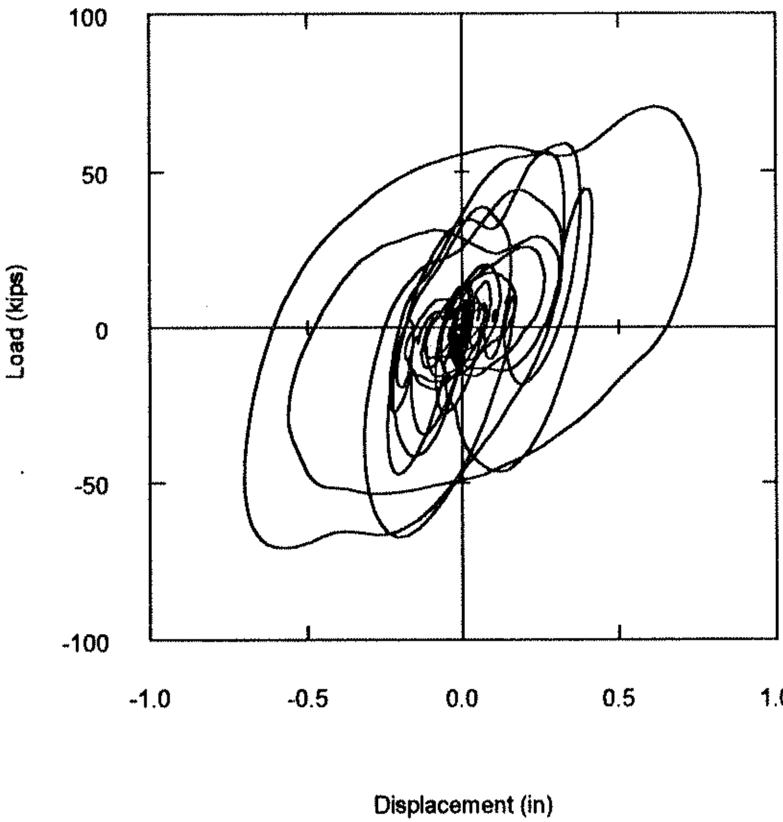
Damper No. 1 Earthquake Test - Dmax = 0.8"

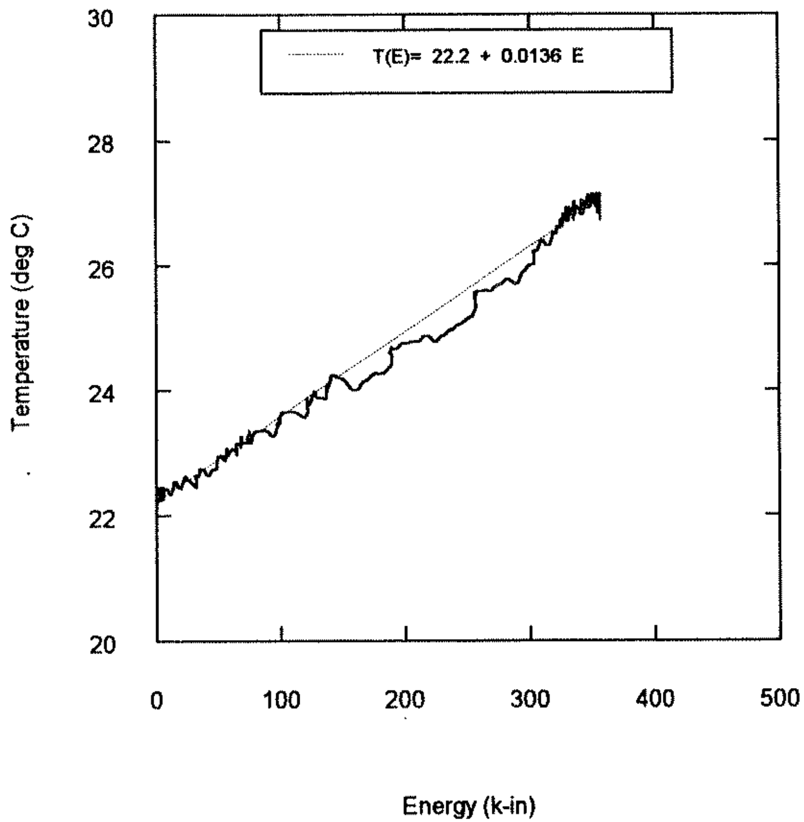
Test date: June 11, 1993 File: d1eq08.txt



Damper No. 1 Earthquake Test - Dmax = 0.8"

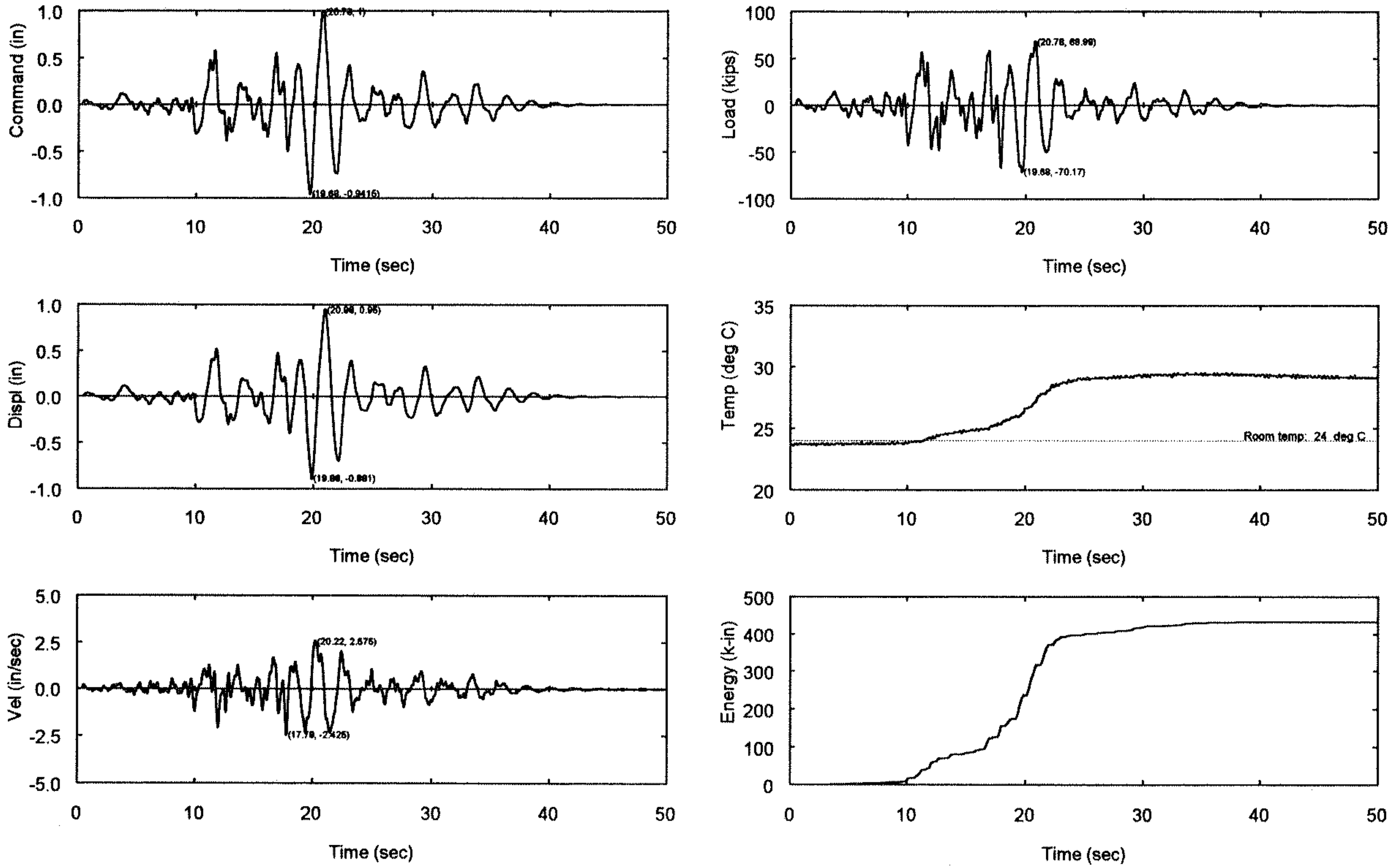
Test date: June 11, 1993 File: d1eq08.txt





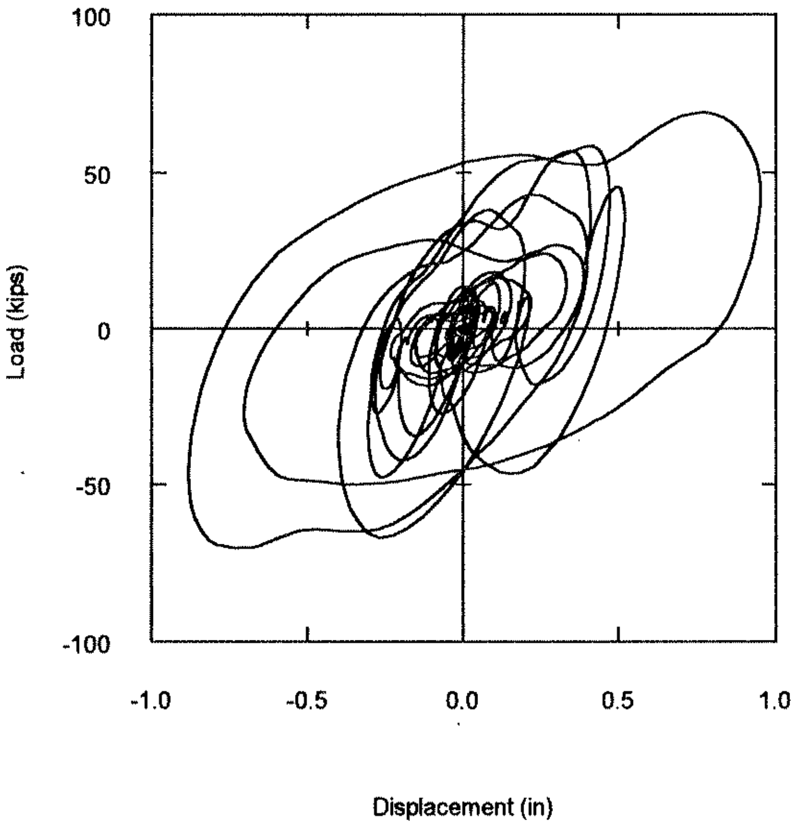
Damper No. 1 Earthquake Test - Dmax = 1.0"

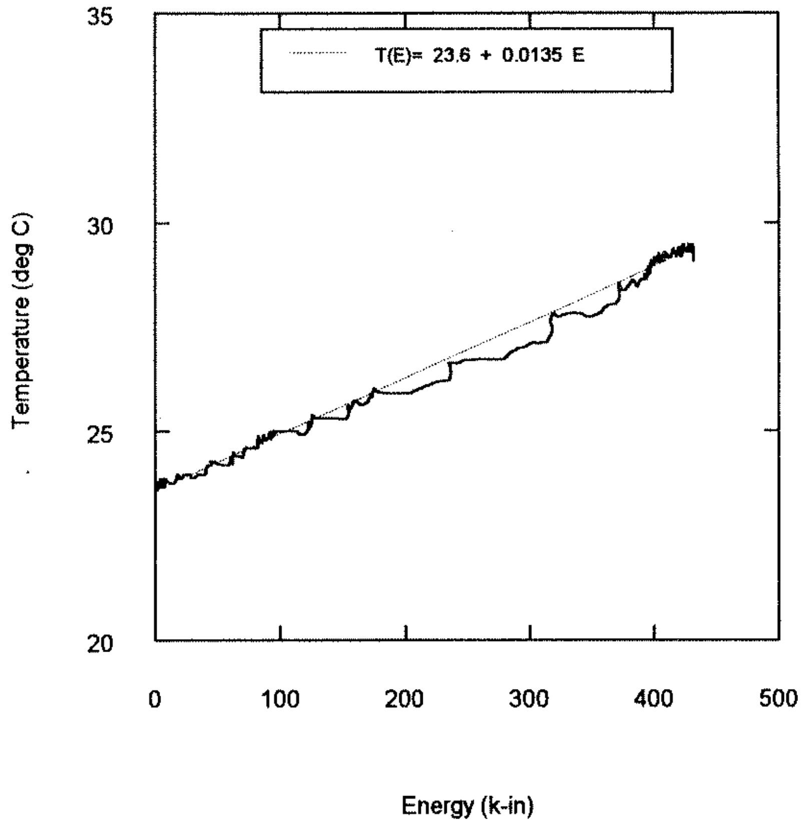
Test date: June 11, 1993 File: d1eq10.txt



Damper No. 1 Earthquake Test - Dmax = 1.0"

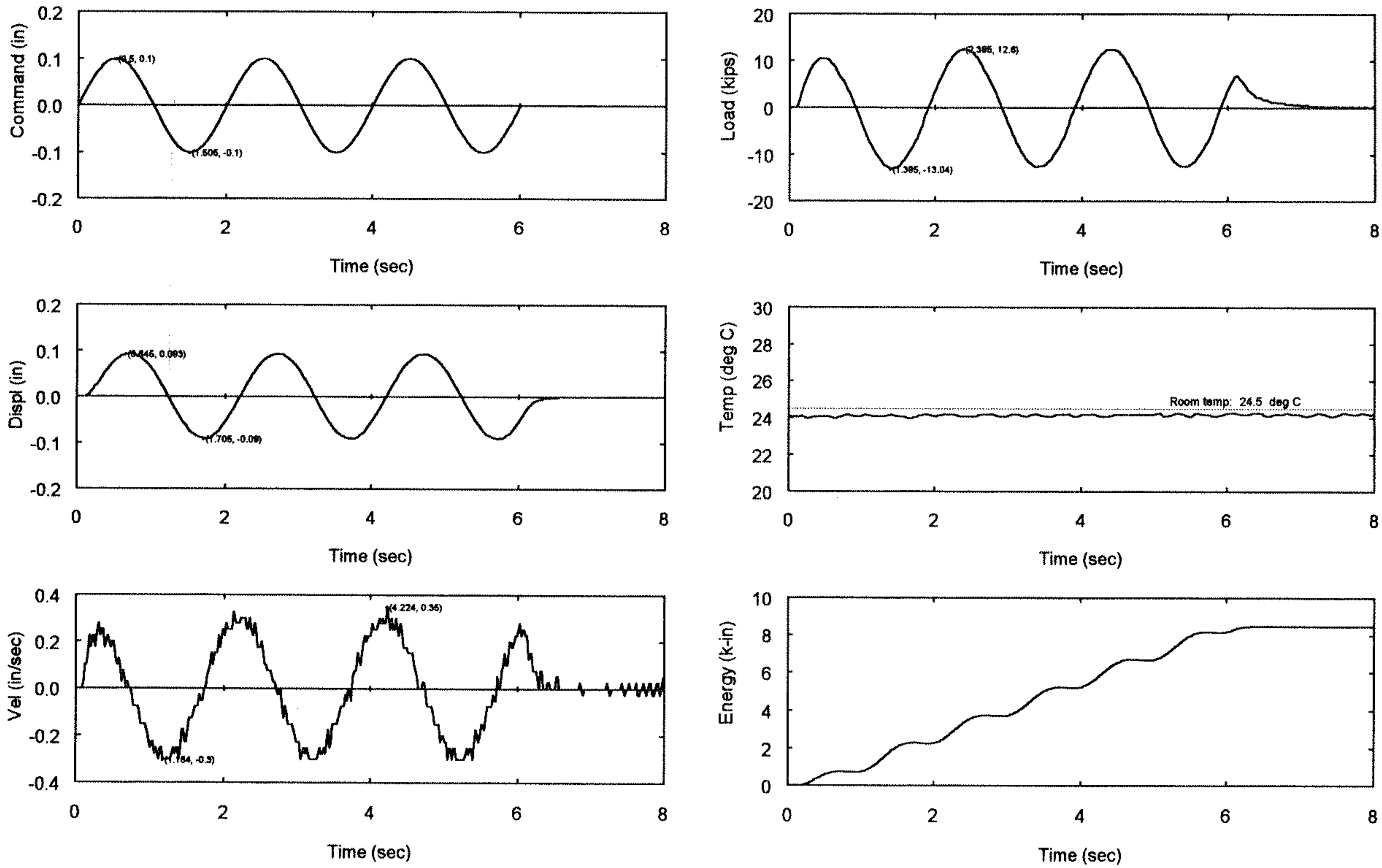
Test date: June 11, 1993 File: d1eq10.txt





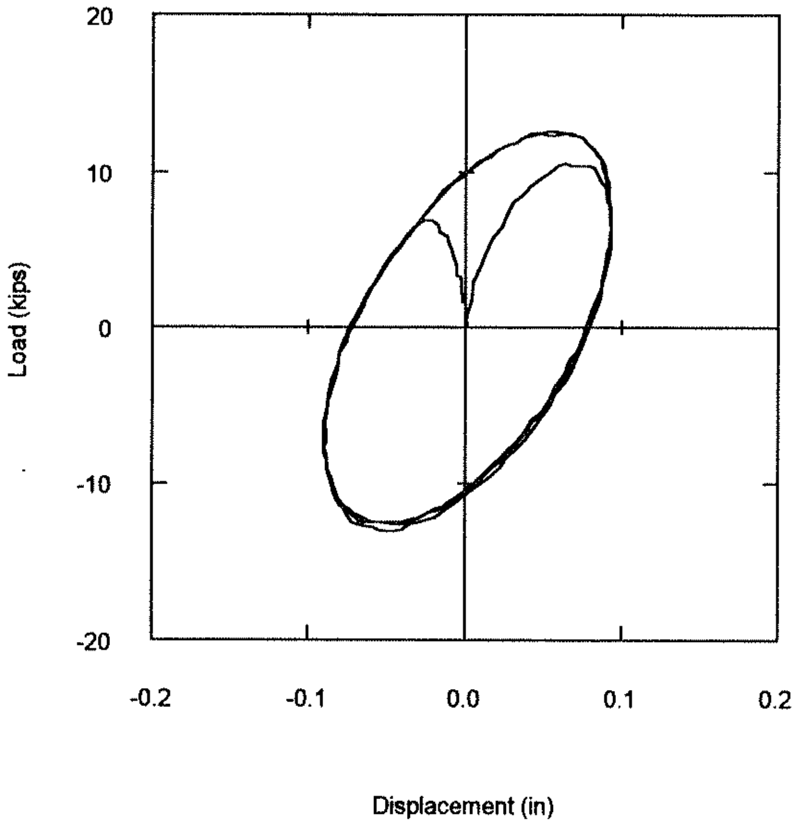
Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.1"

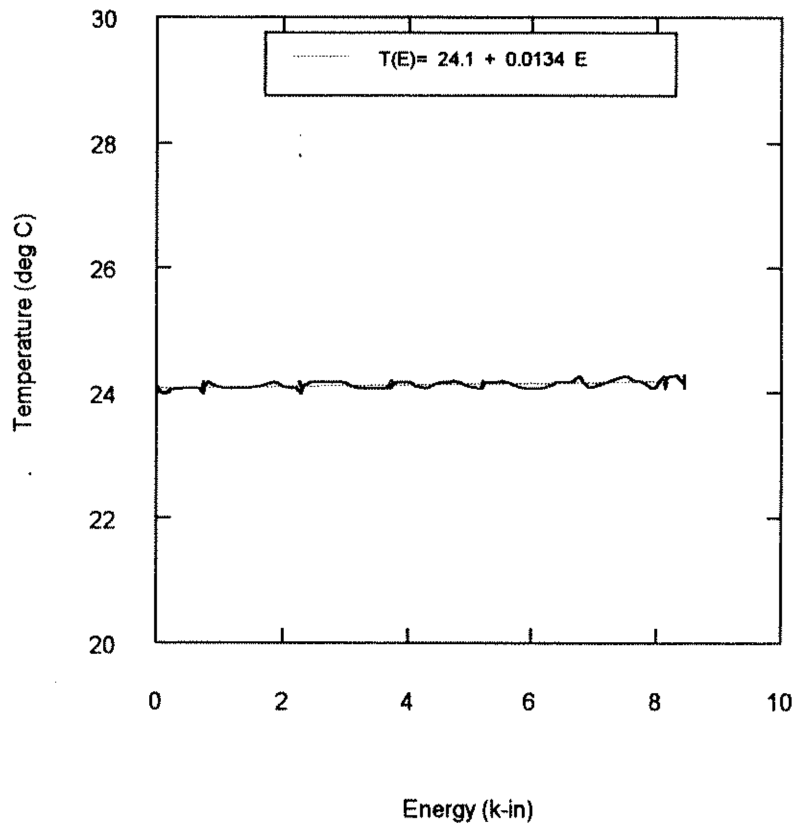
Test date: June 11, 1993 File: d1h301.txt



Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.1"

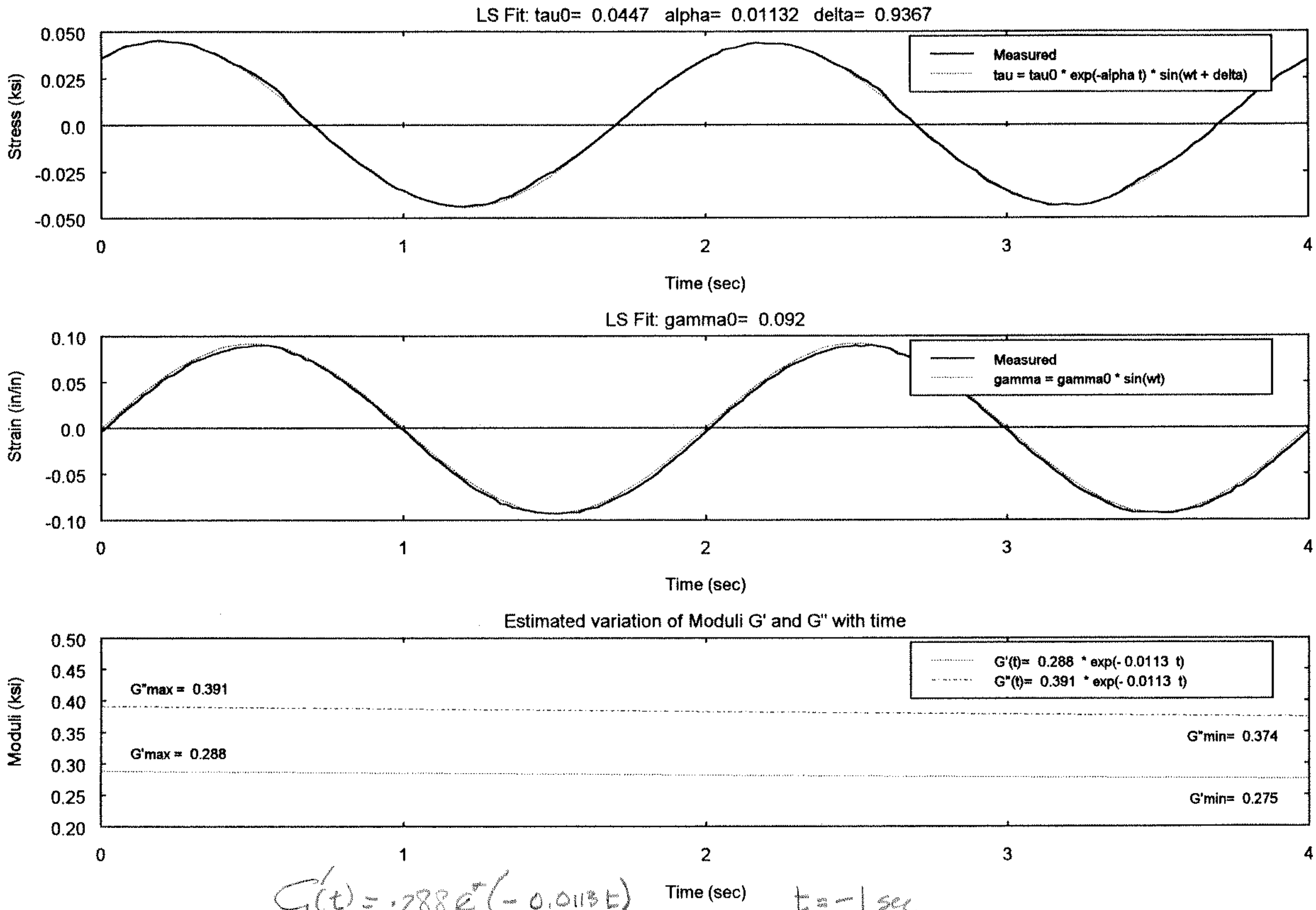
Test date: June 11, 1993 File: d1h301.txt





Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.1"

Test date: June 11, 1993 File: d1h301.txt

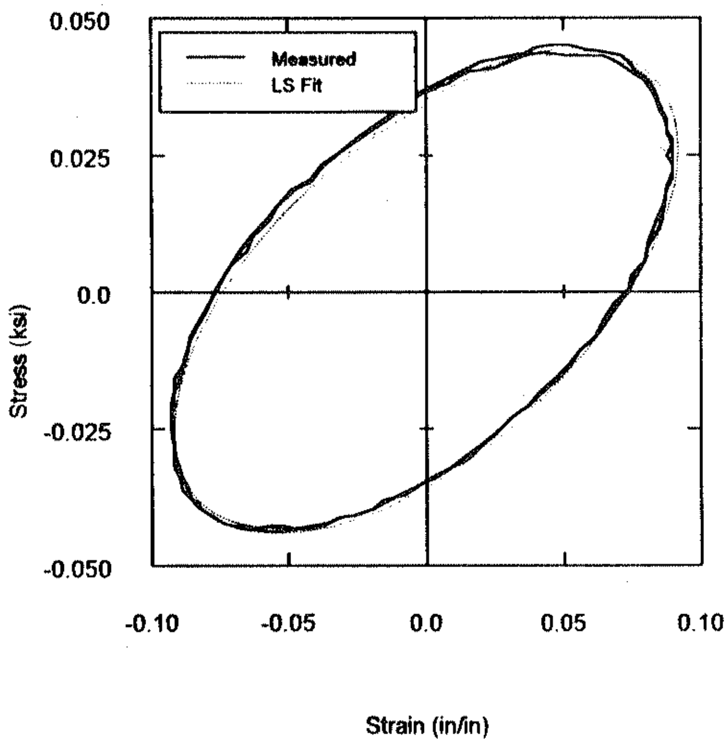


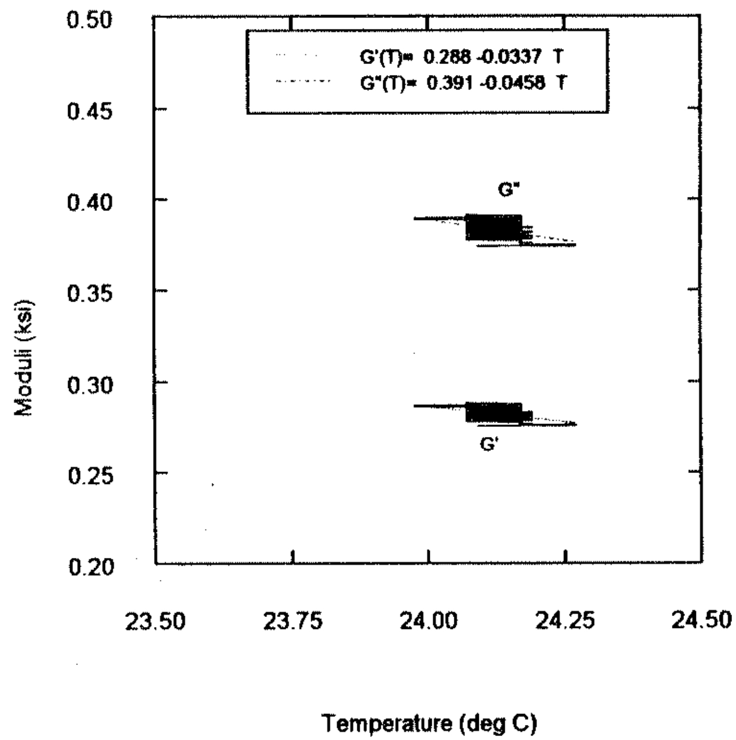
$G'(t) = .288 e^{(-0.0113t)}$ $t = -1$ sec

$G'_0 = .288 e^{(+.0113)} = .291$ $G''_0 = .395$

Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.1"

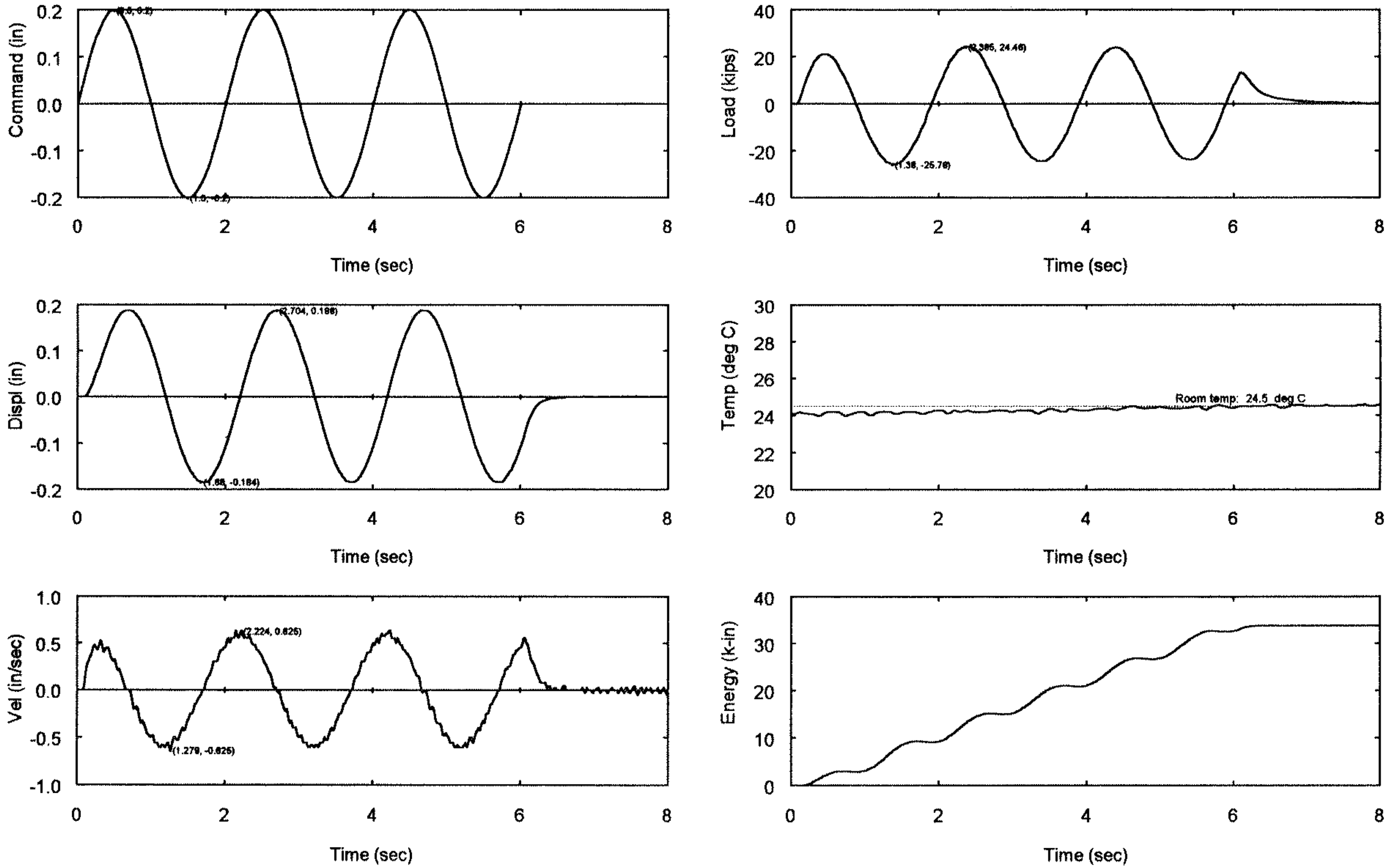
Test date: June 11, 1993 File: d1h301.txt





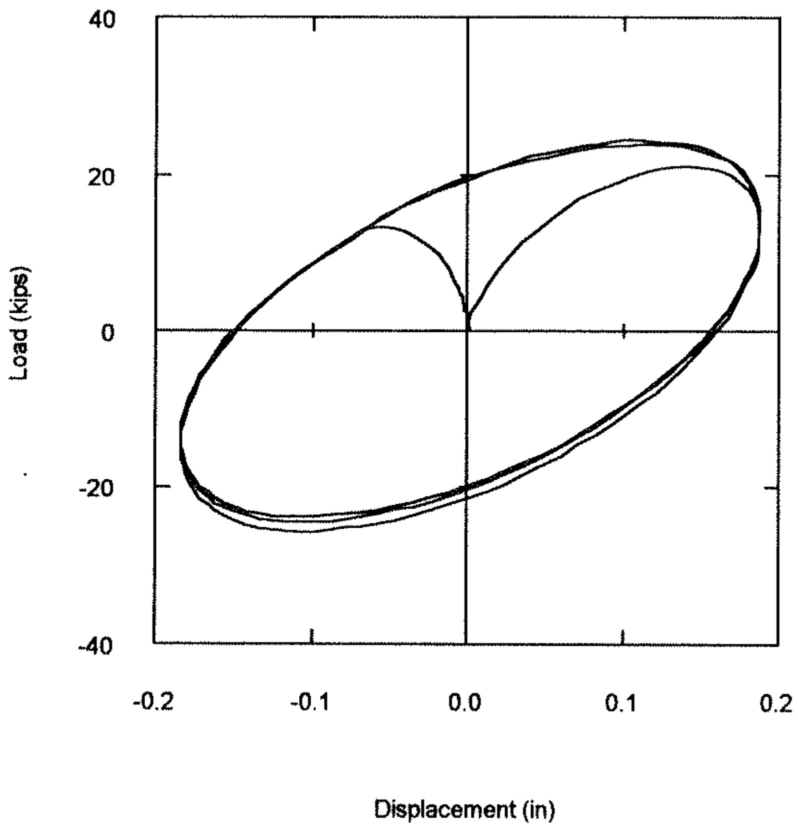
Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.2"

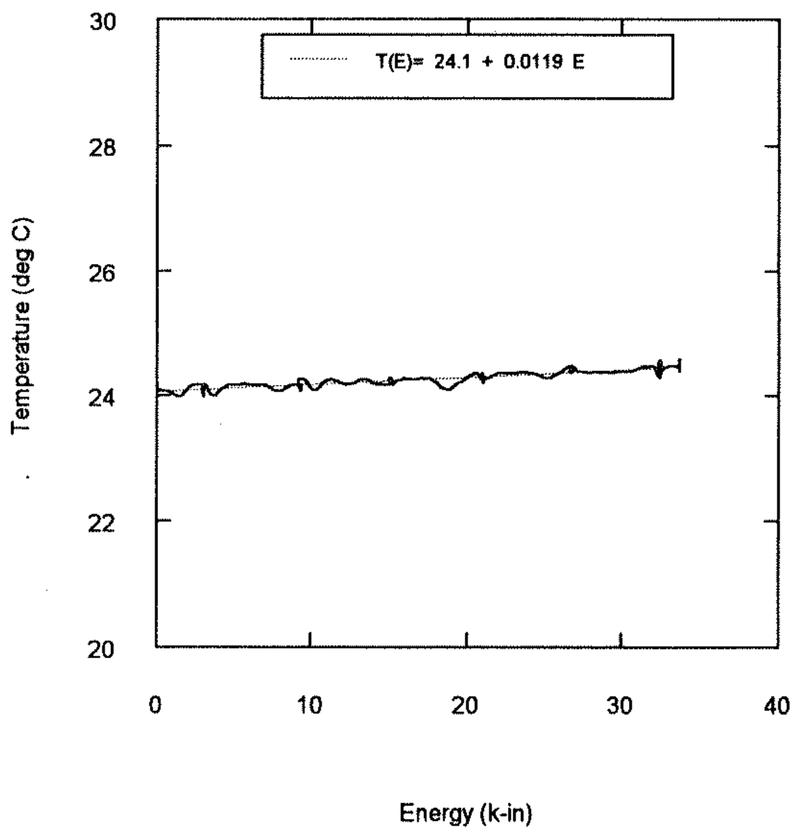
Test date: June 11, 1993 File: d1h302.txt



Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.2"

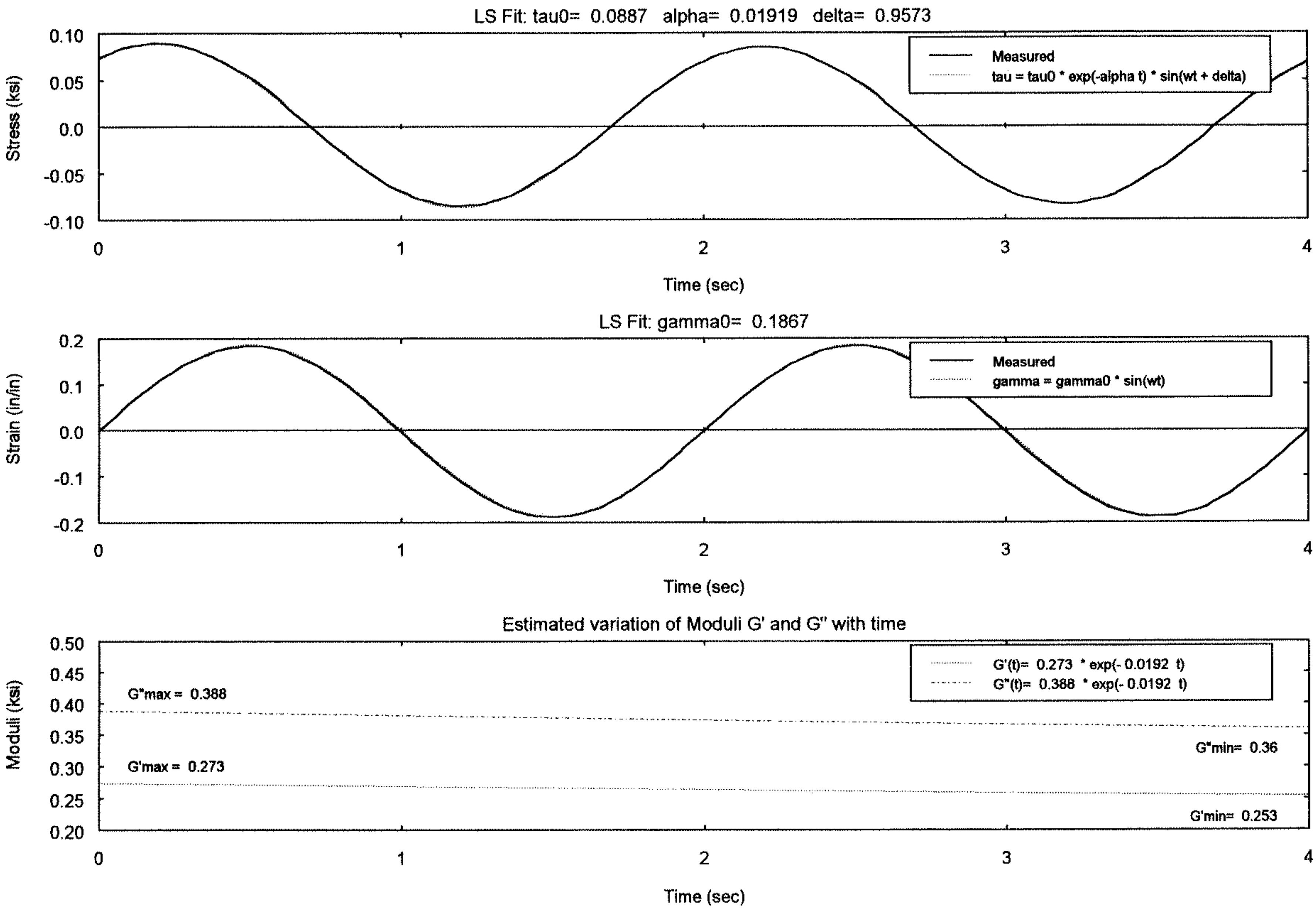
Test date: June 11, 1993 File: d1h302.txt





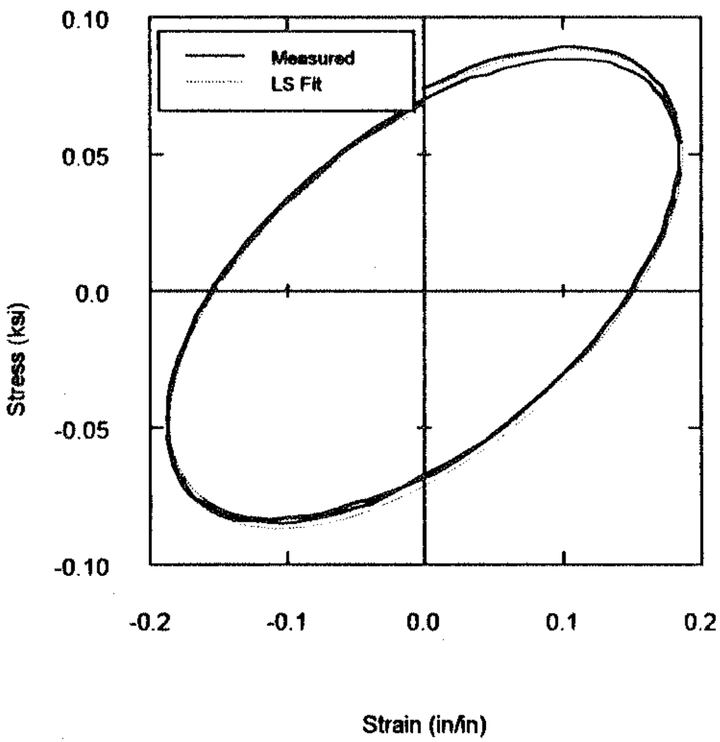
Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.2"

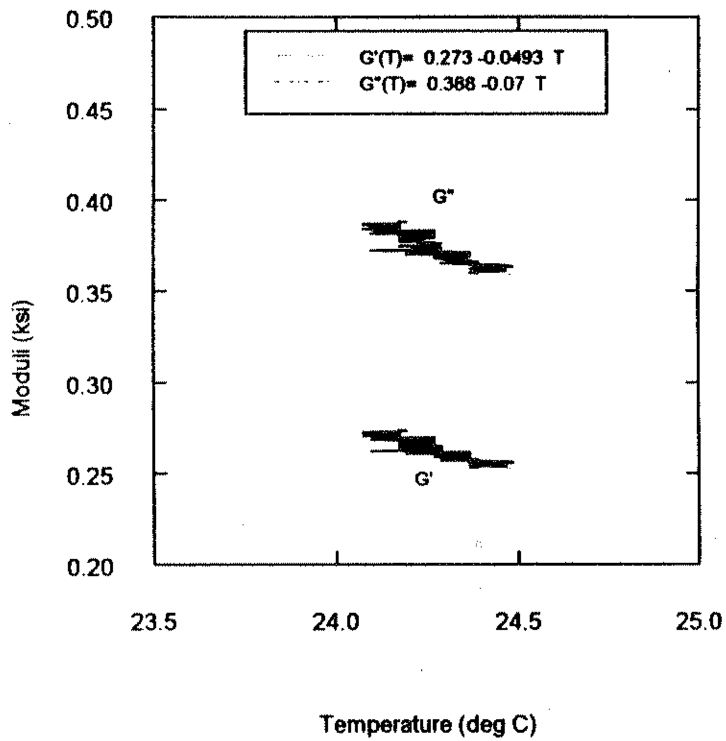
Test date: June 11, 1993 File: d1h302.txt



Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.2"

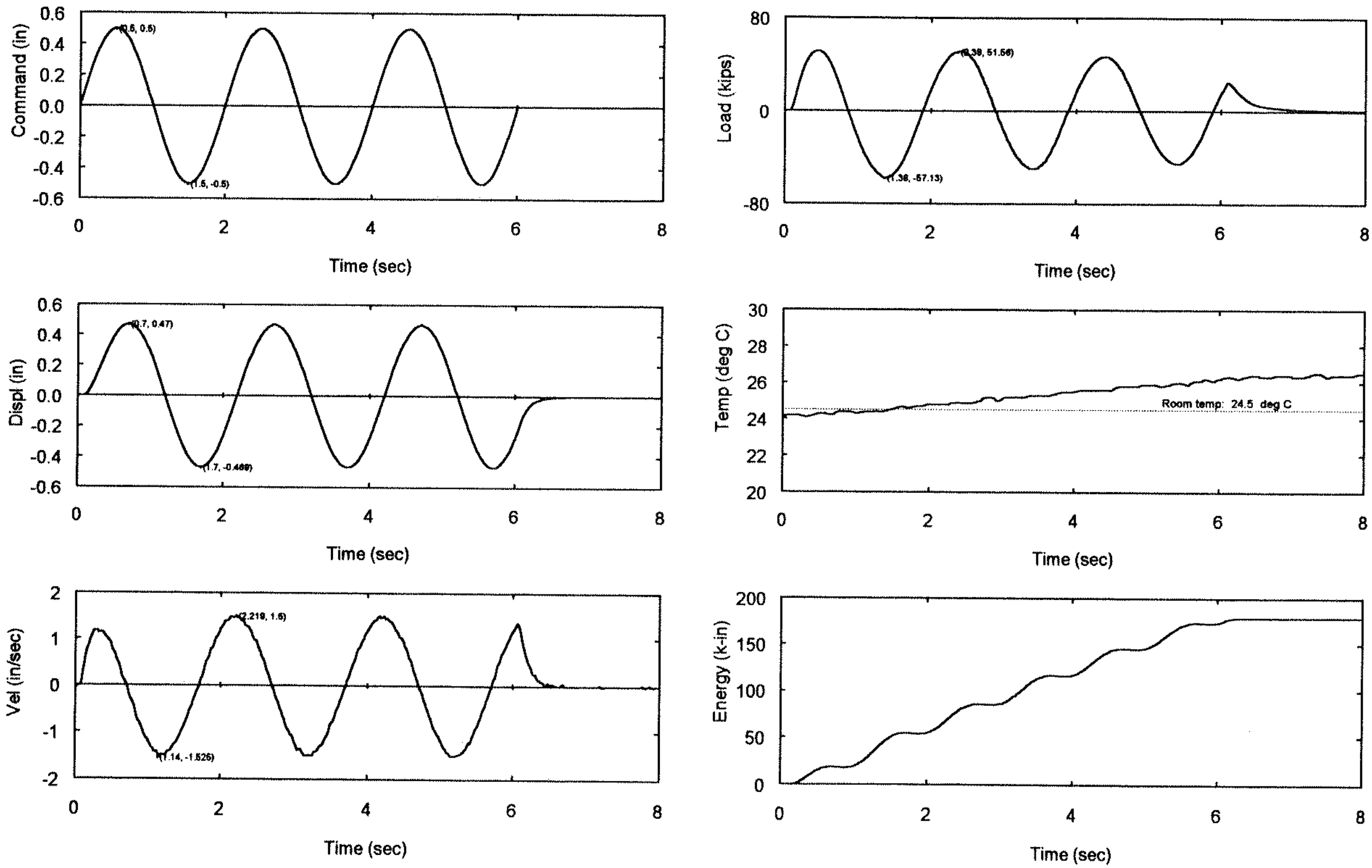
Test date: June 11, 1993 File: d1h302.txt





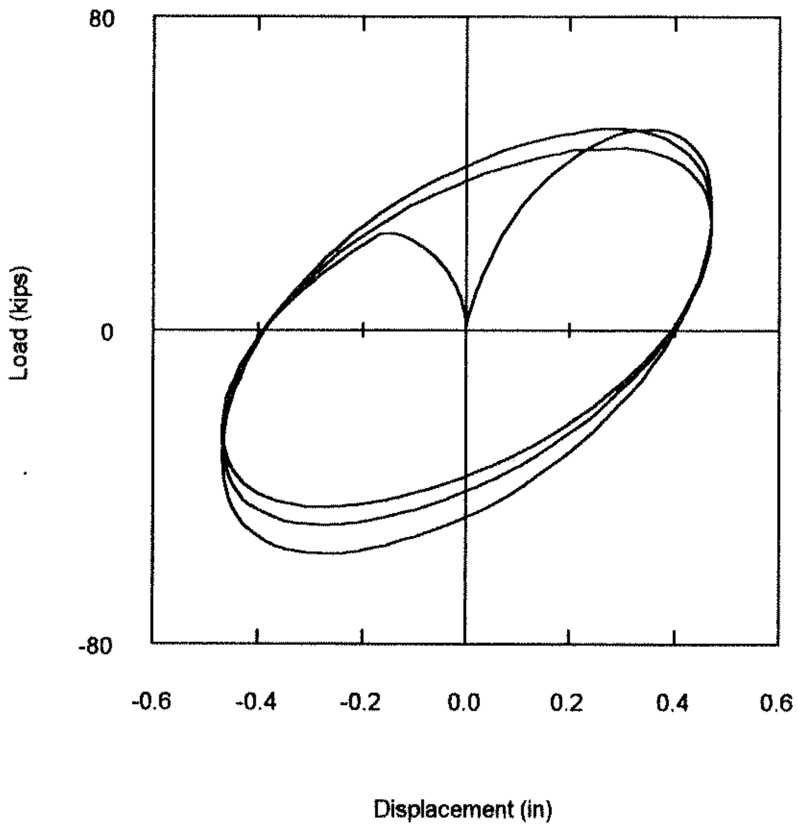
Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.5"

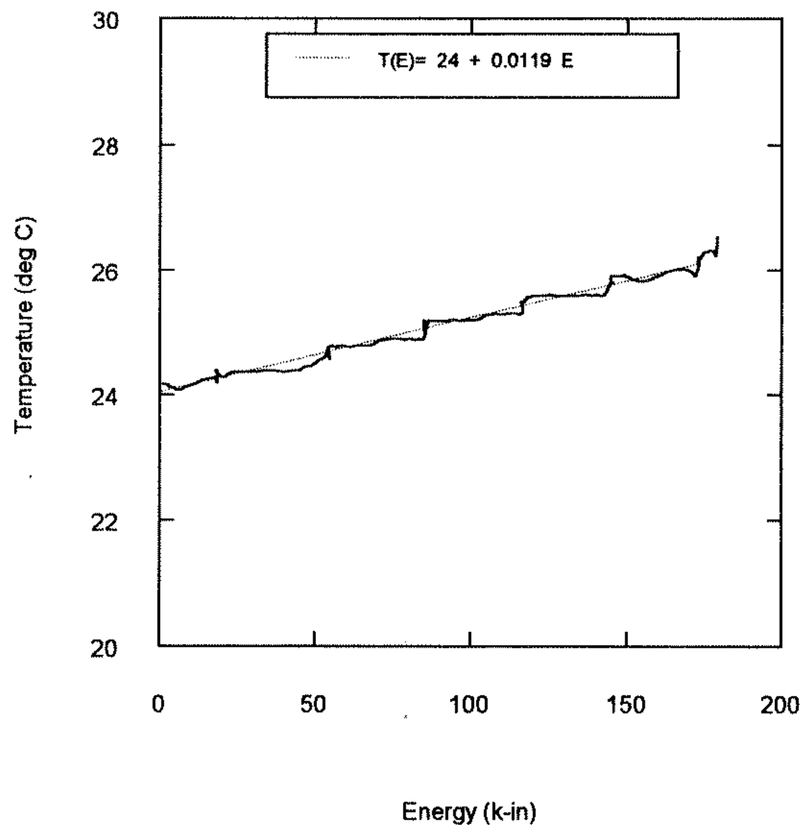
Test date: June 11, 1993 File: d1h305.txt



Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.5"

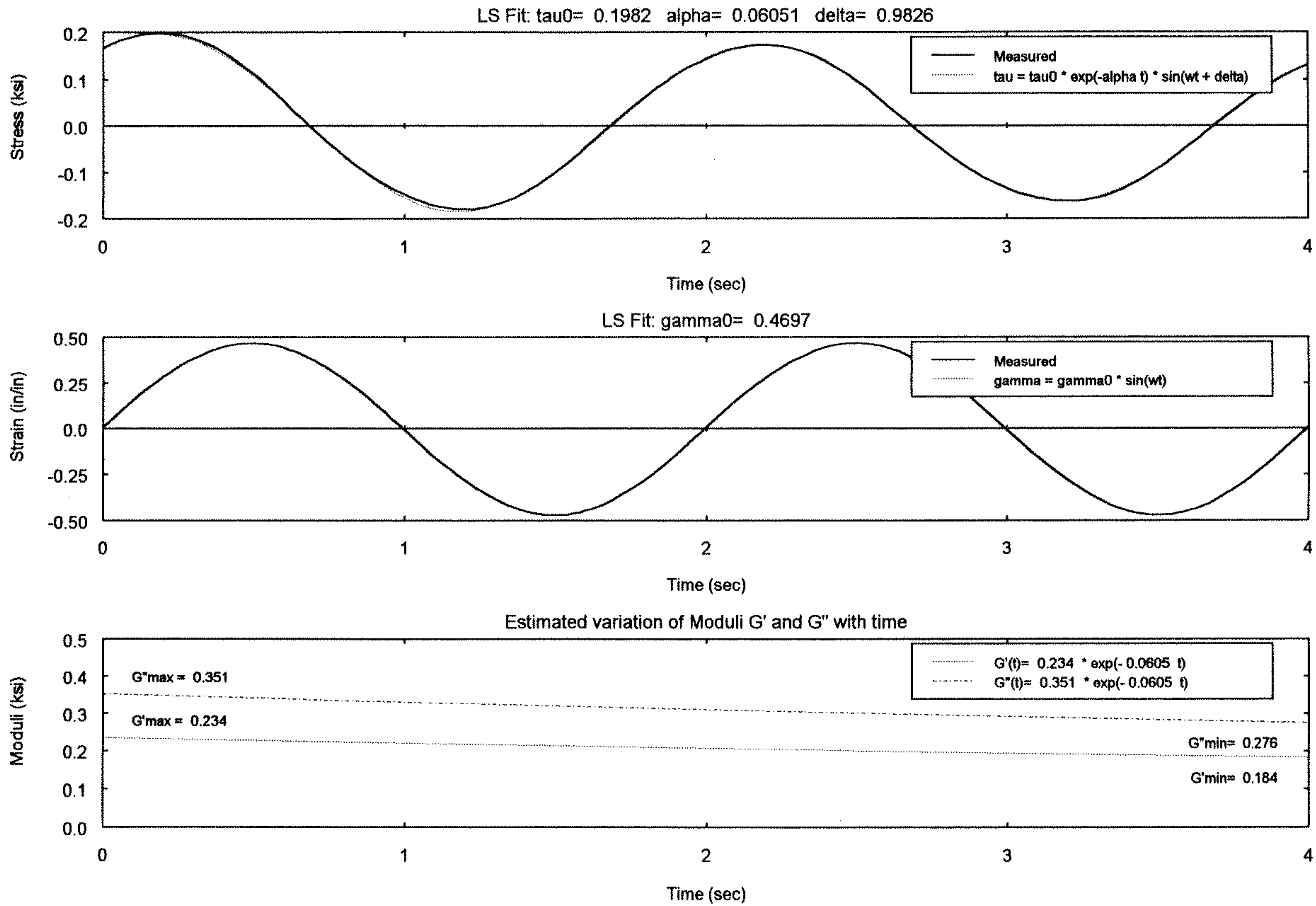
Test date: June 11, 1993 File: d1h305.txt





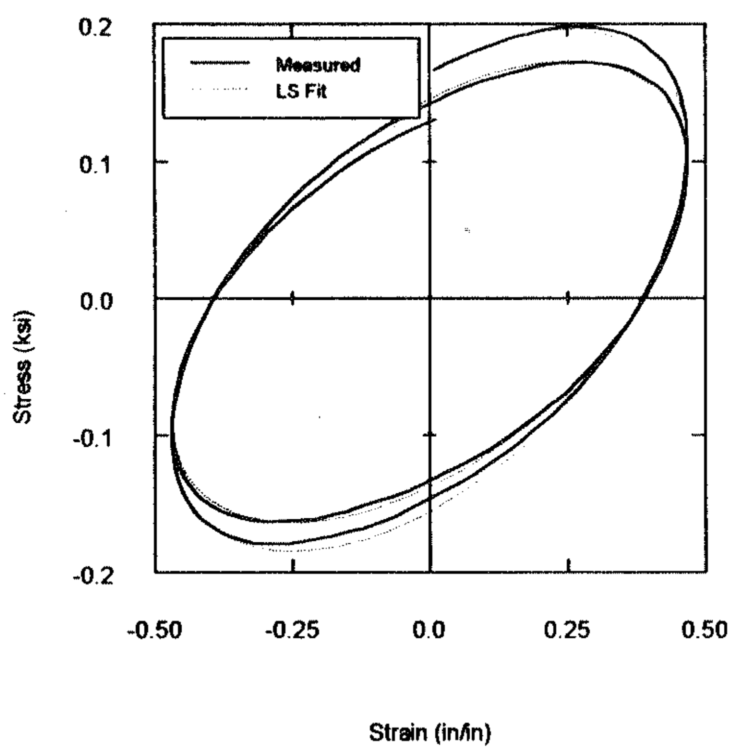
Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.5"

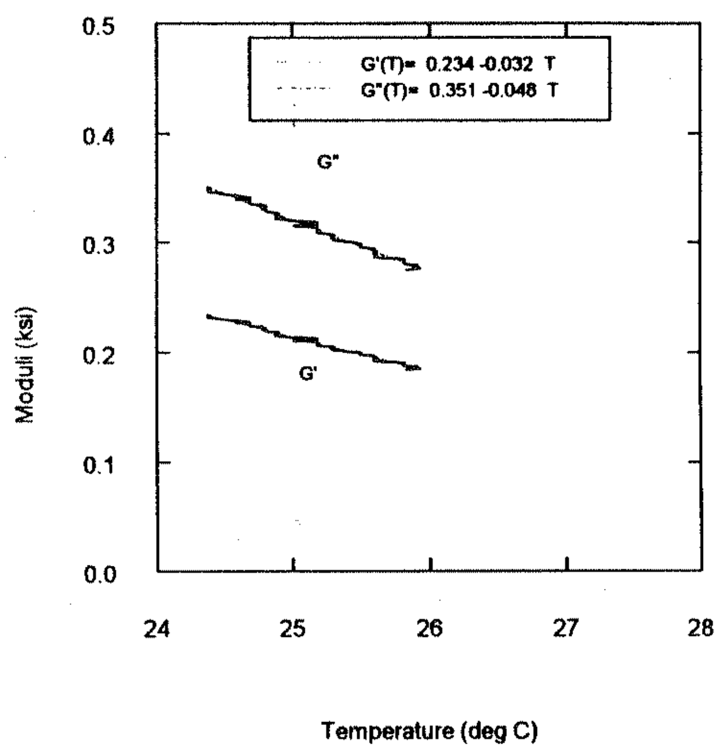
Test date: June 11, 1993 File: d1h305.txt



Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.5"

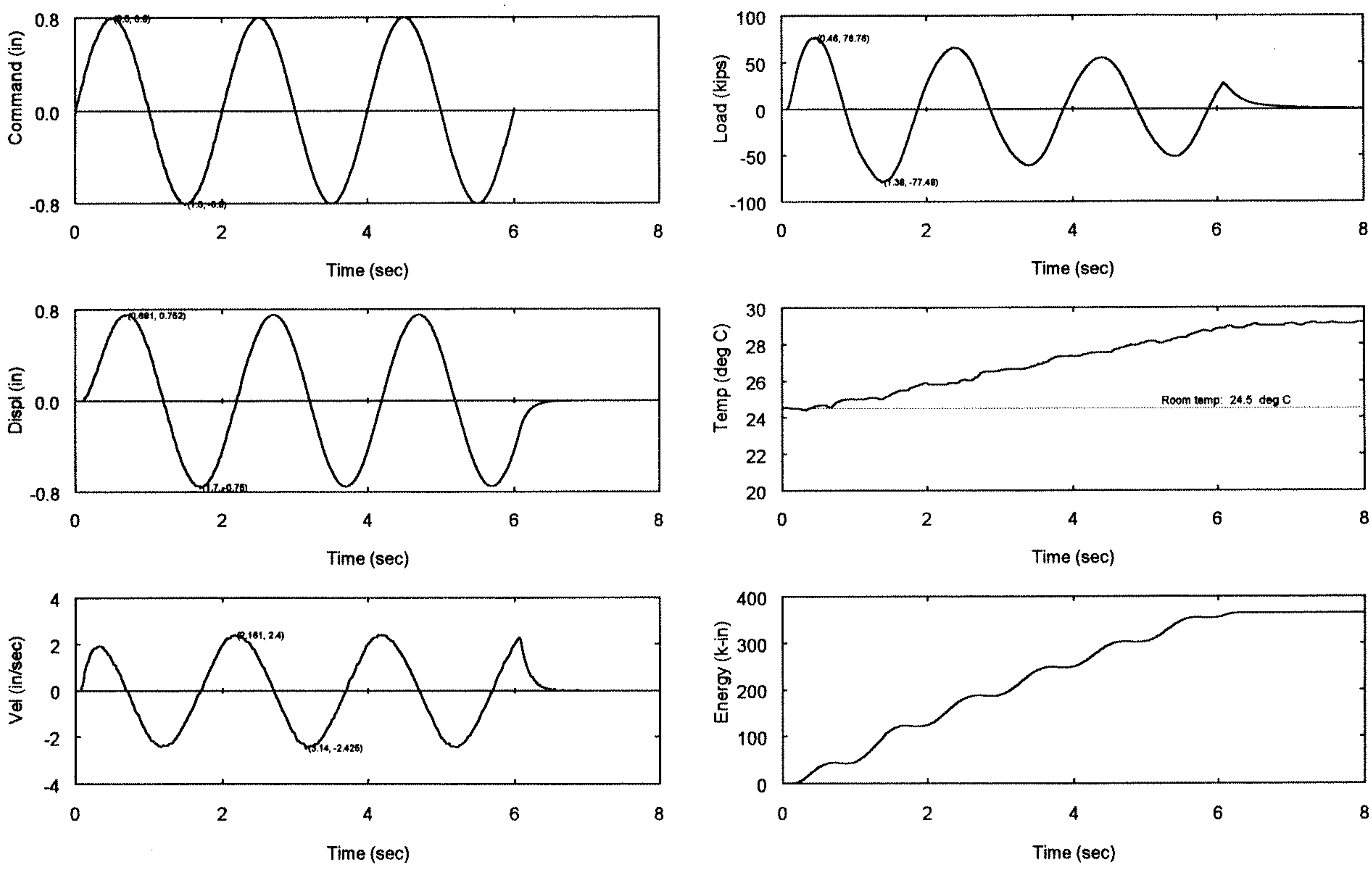
Test date: June 11, 1993 File: d1h305.txt





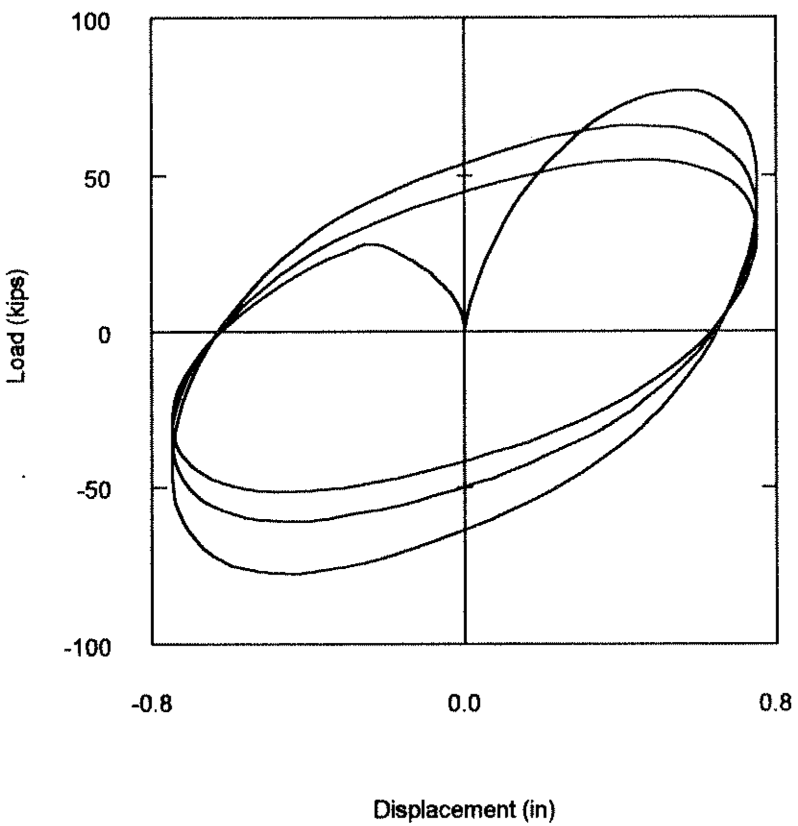
Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.8"

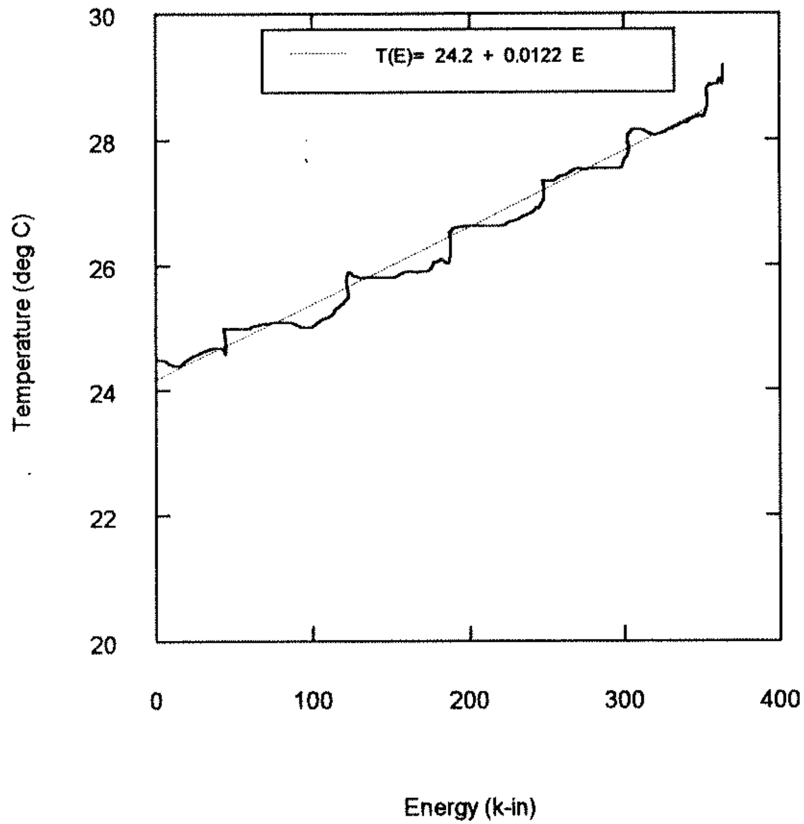
Test date: June 11, 1993 File: d1h308.txt



Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.8"

Test date: June 11, 1993 File: d1h308.txt

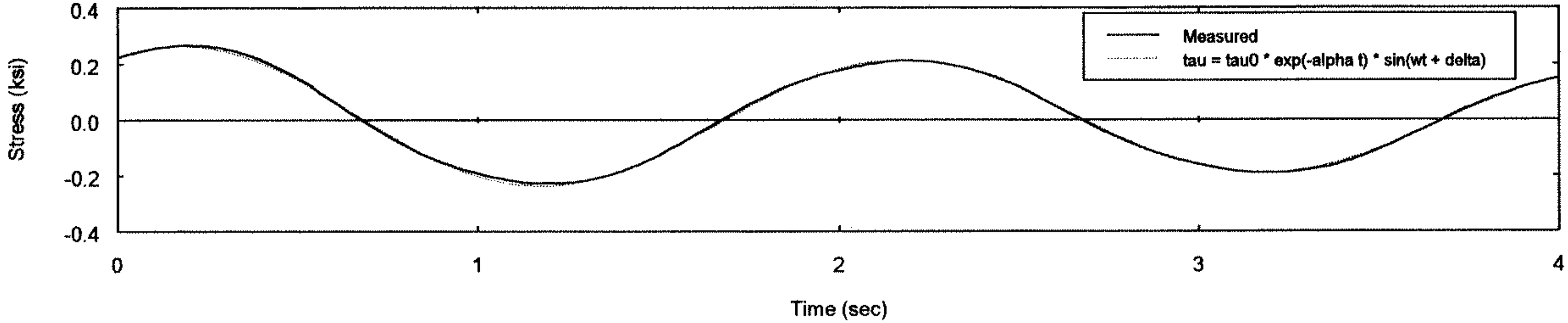




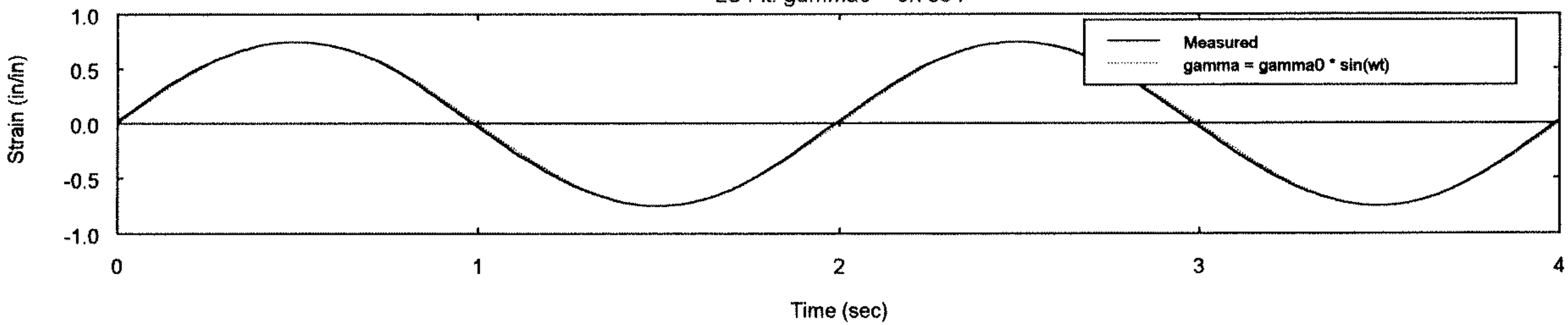
Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.8"

Test date: June 11, 1993 File: d1h308.txt

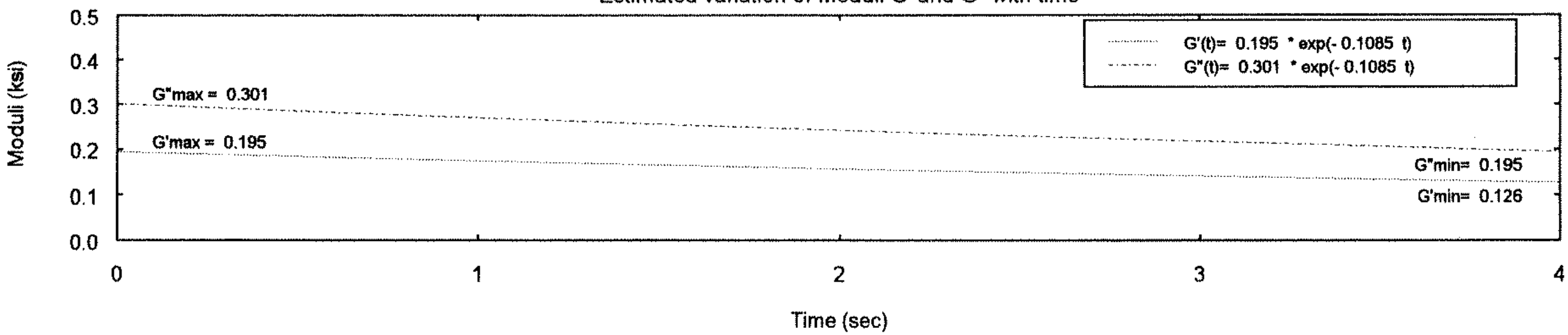
LS Fit: tau0= 0.2701 alpha= 0.1085 delta= 0.9962



LS Fit: gamma0= 0.7534

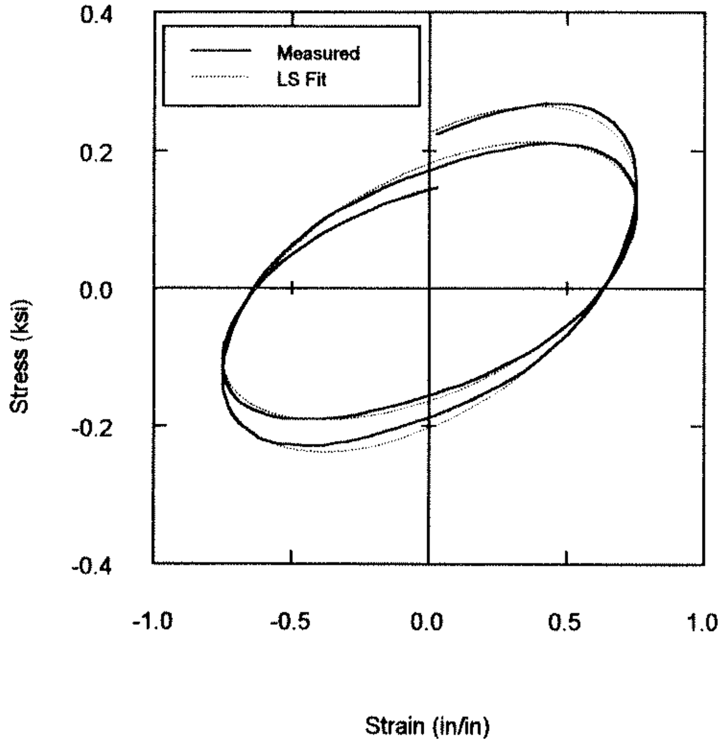


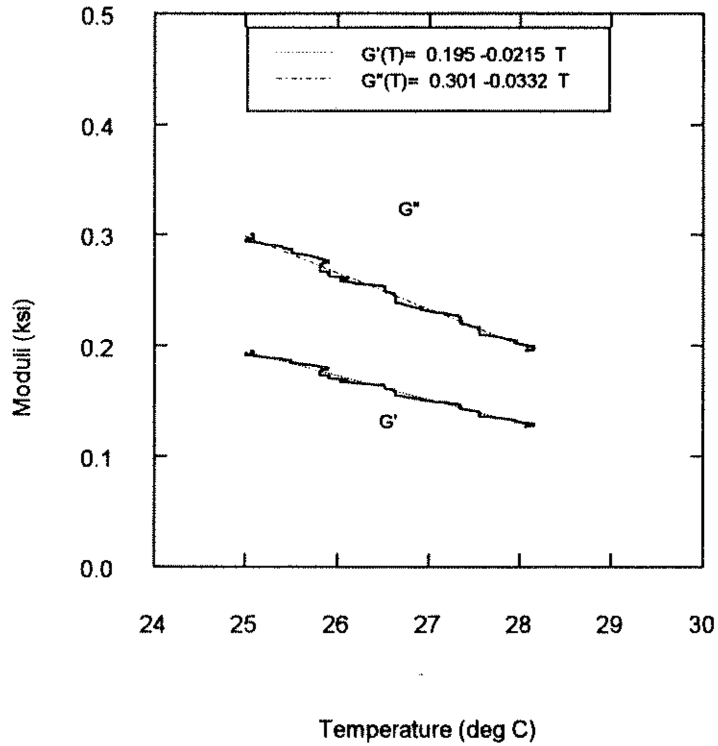
Estimated variation of Moduli G' and G" with time



Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.8"

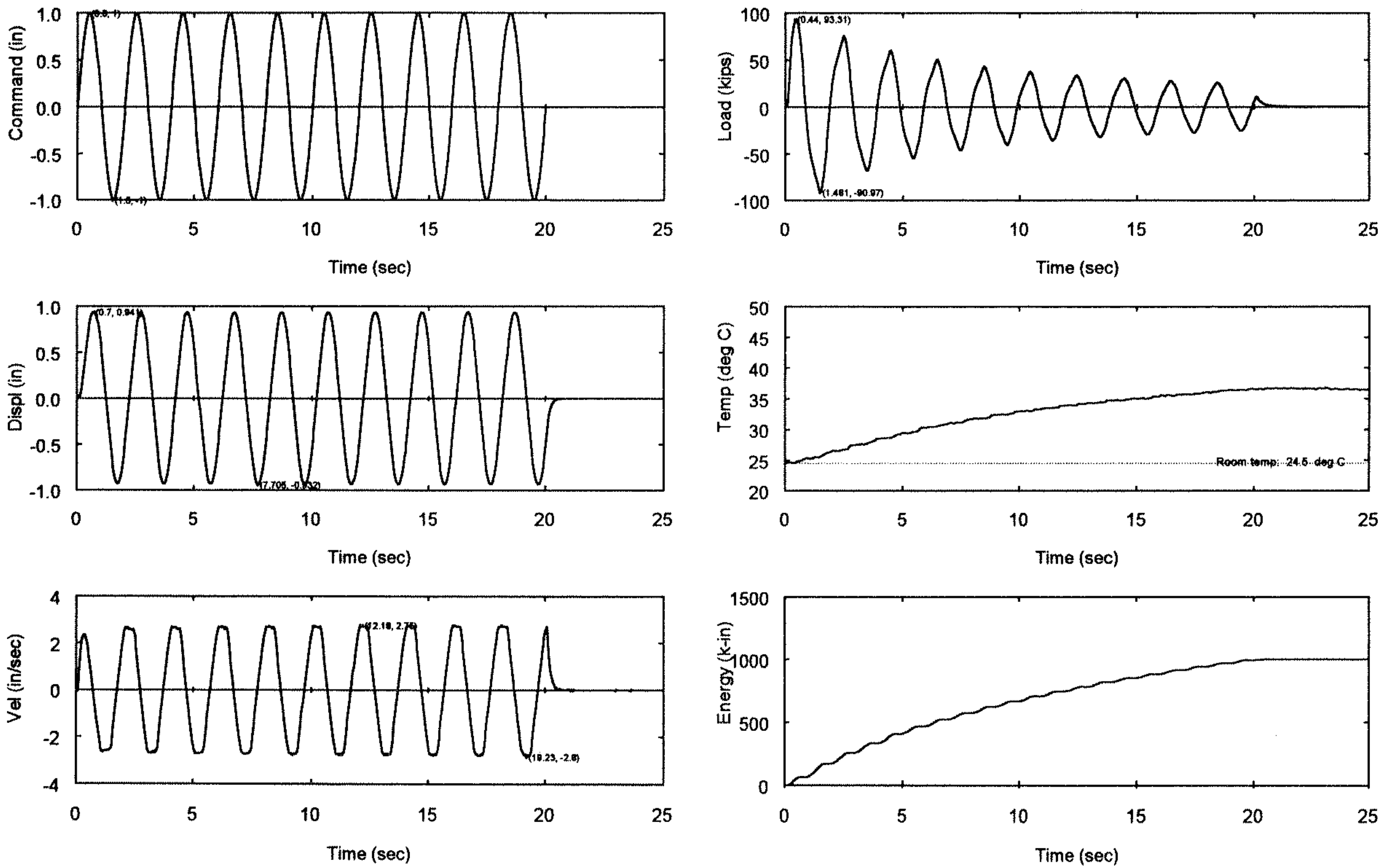
Test date: June 11, 1993 File: d1h308.txt





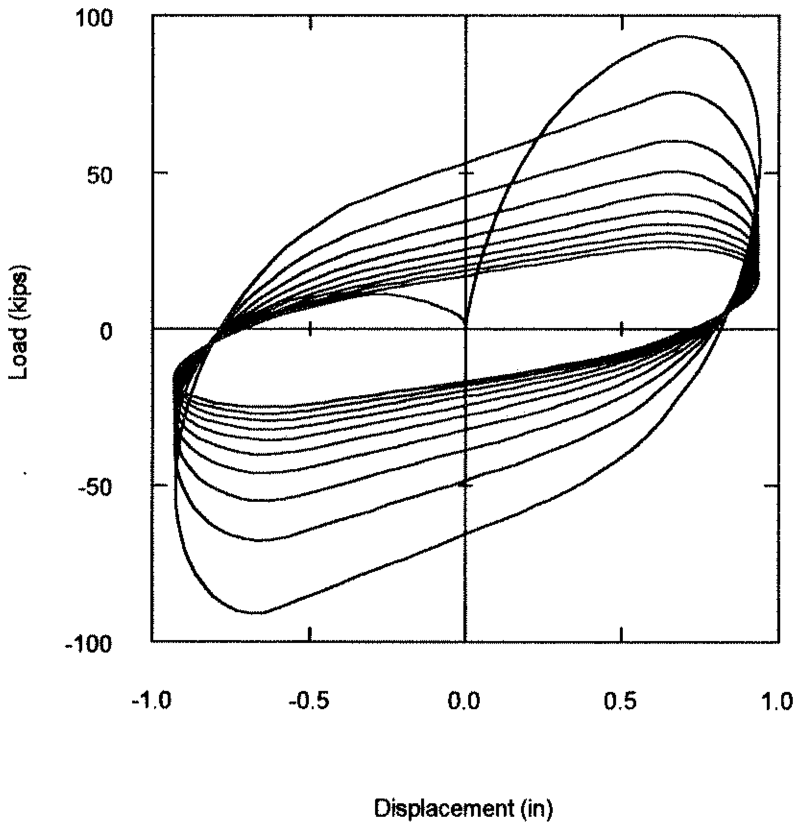
Damper No. 1 Harmonic 10 Cycle Test - Dmax = 1.0"

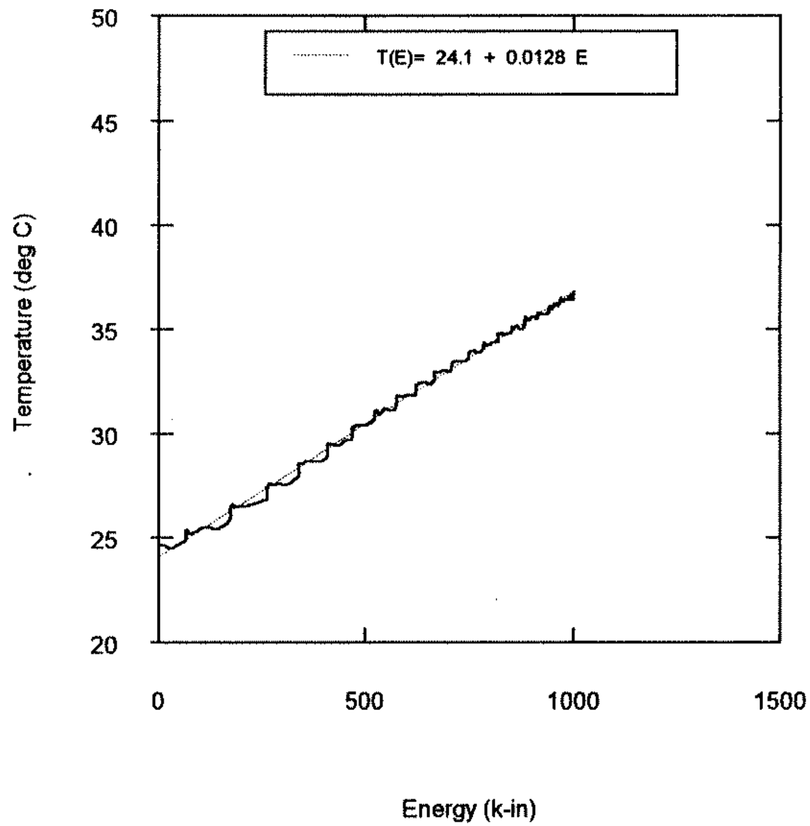
Test date: June 11, 1993 File: d1h1010.txt



Damper No. 1 Harmonic 10 Cycle Test - Dmax = 1.0"

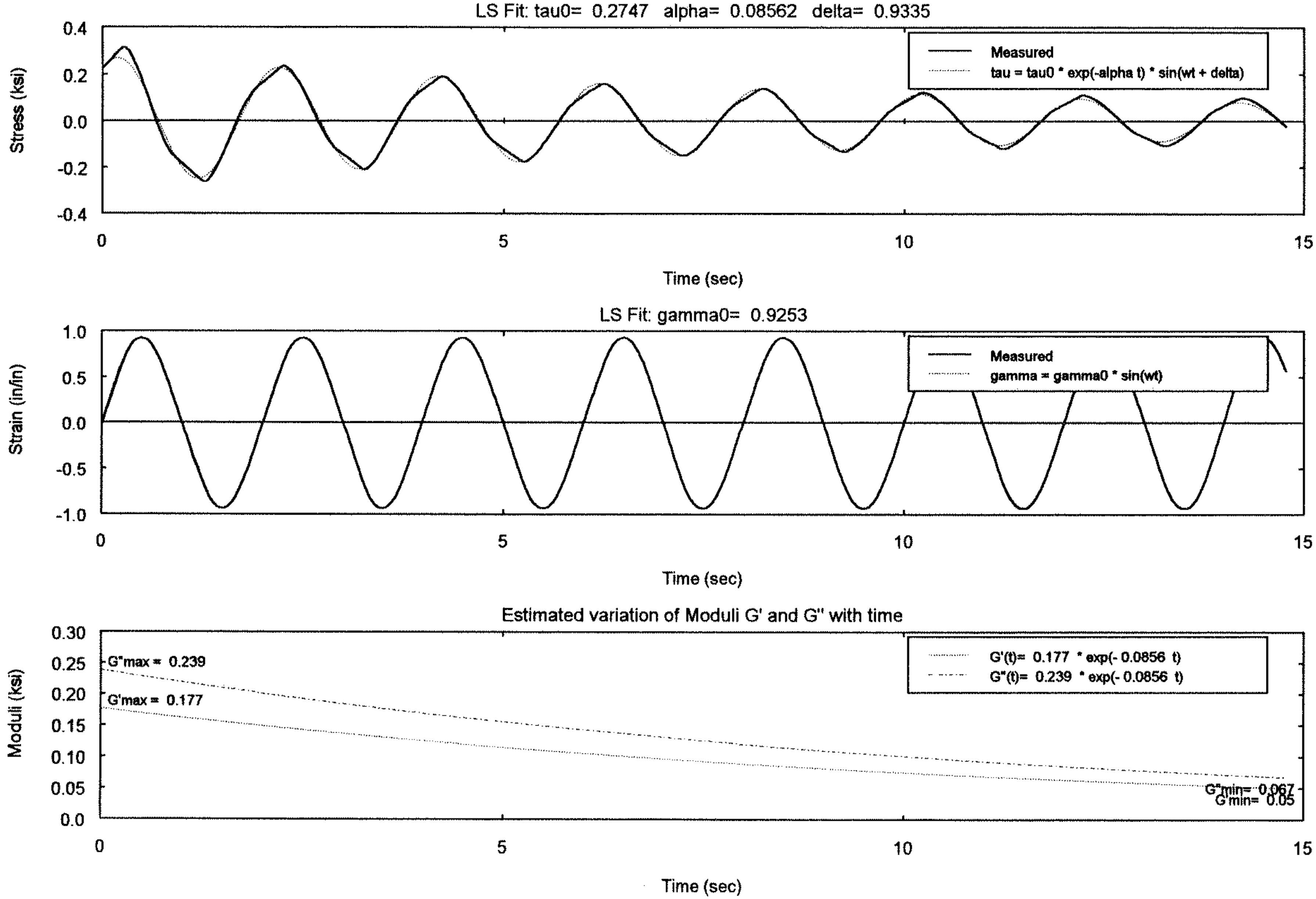
Test date: June 11, 1993 File: d1h1010.txt





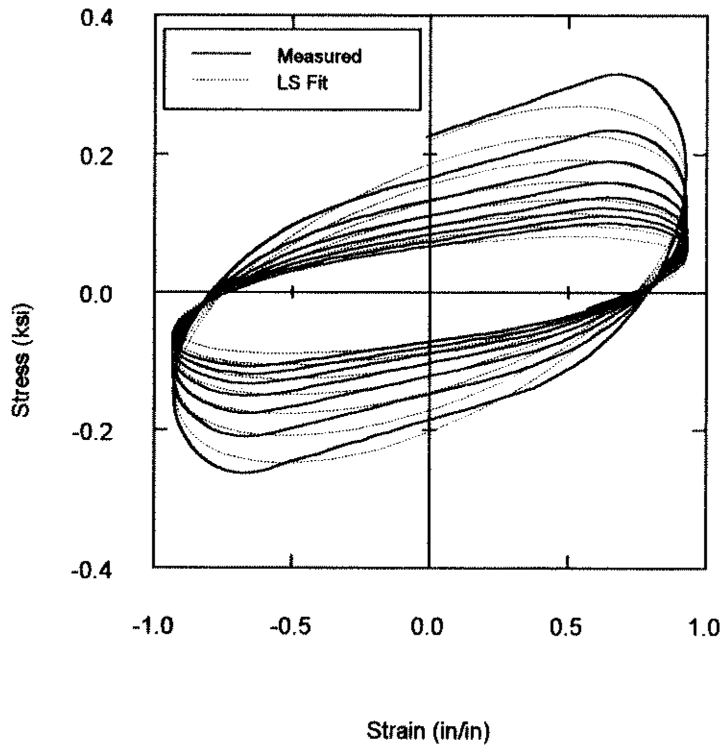
Damper No. 1 Harmonic 10 Cycle Test - Dmax = 1.0"

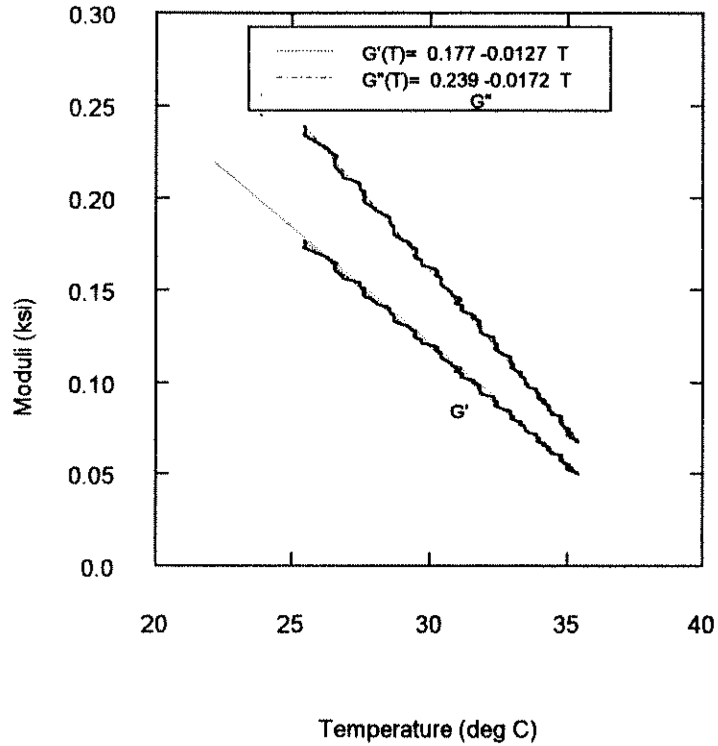
Test date: June 11, 1993 File: d1h1010.txt



Damper No. 1 Harmonic 10 Cycle Test - Dmax = 1.0"

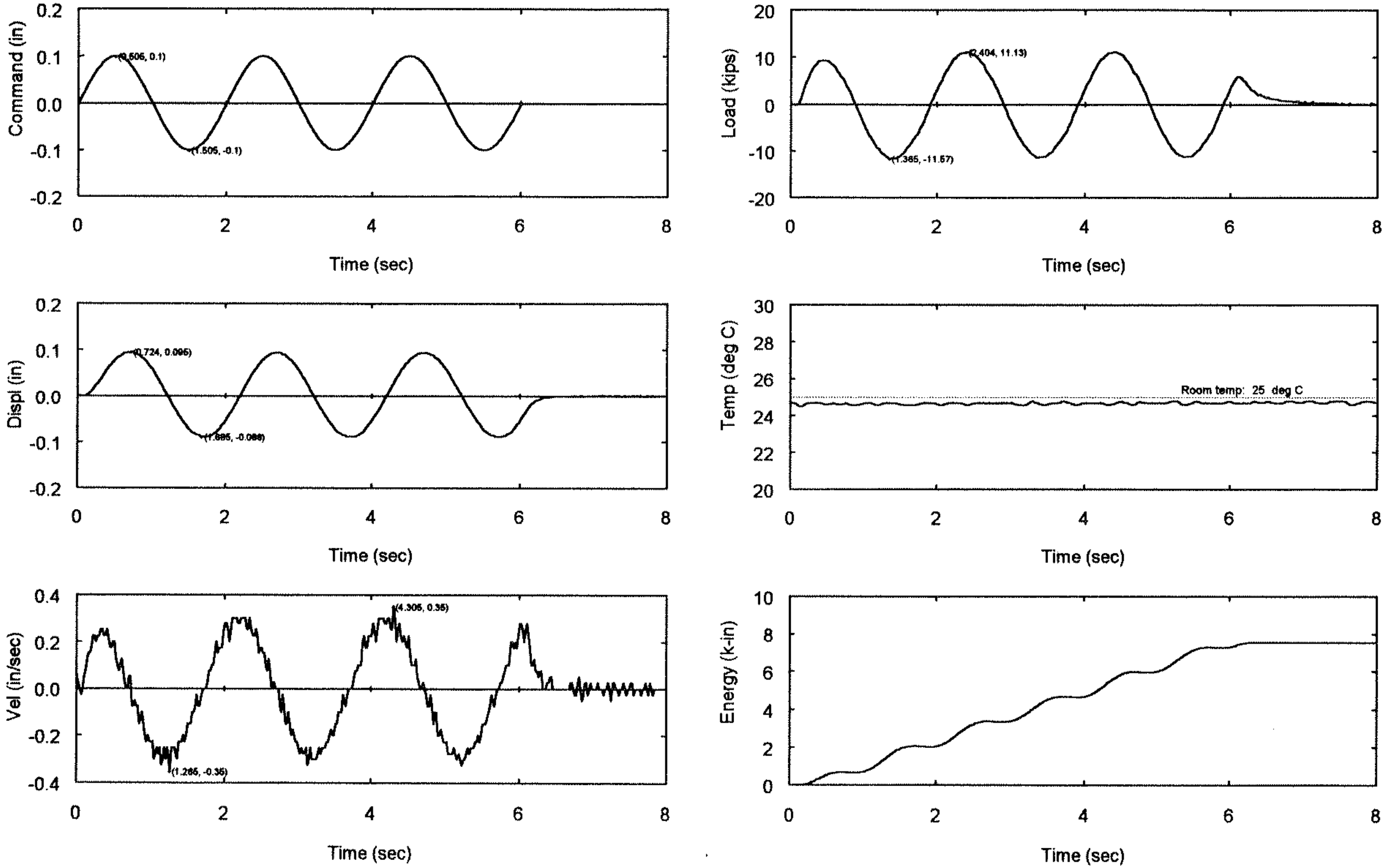
Test date: June 11, 1993 File: d1h1010.txt





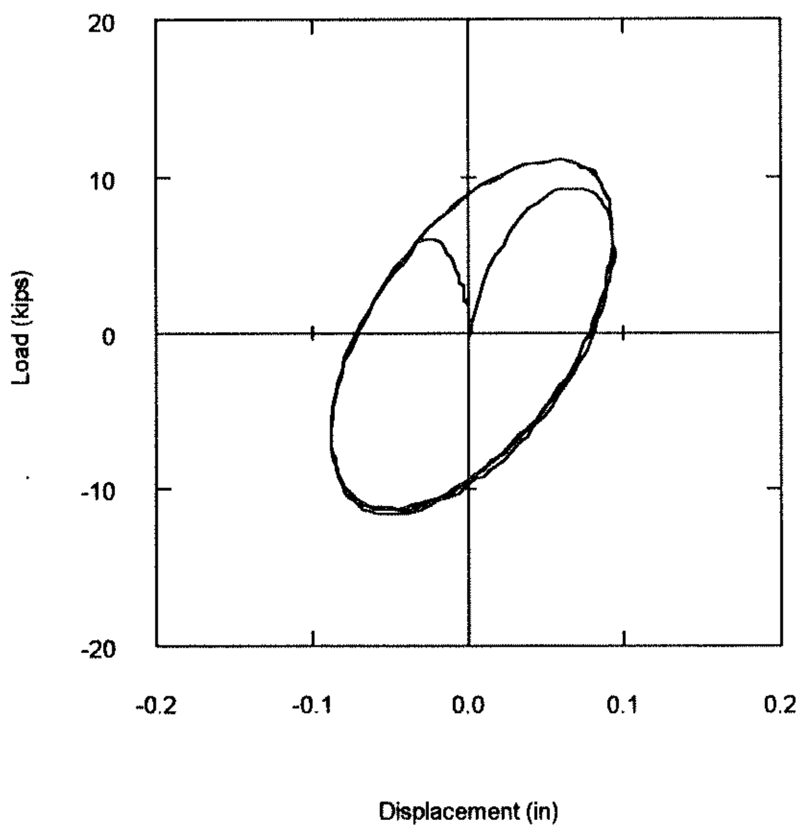
Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.1" (2nd test)

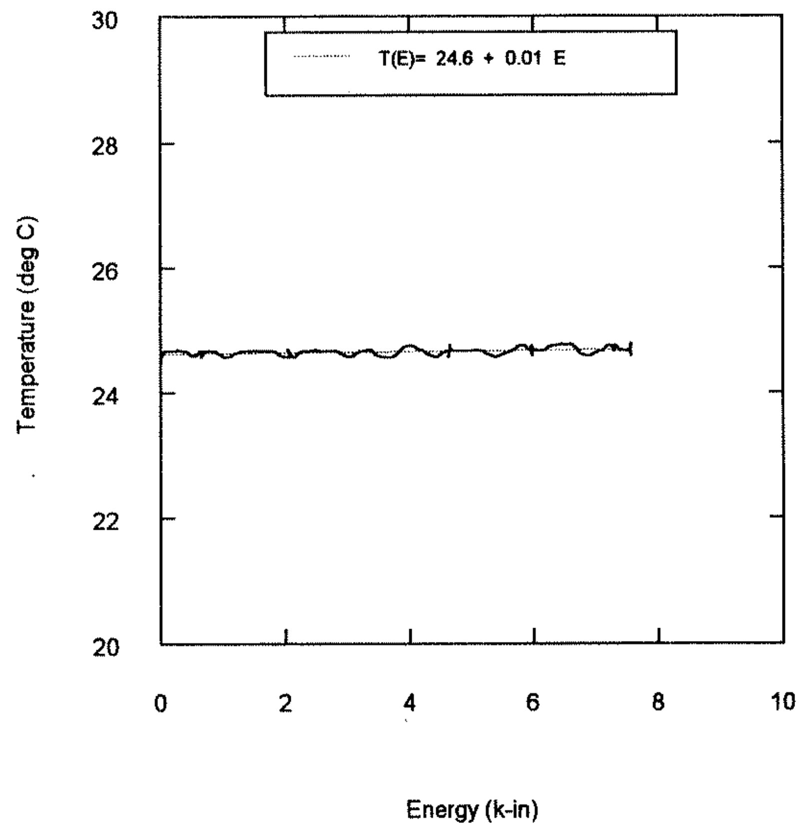
Test date: June 11, 1993 File: d1h301a.txt



Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.1" (2nd test)

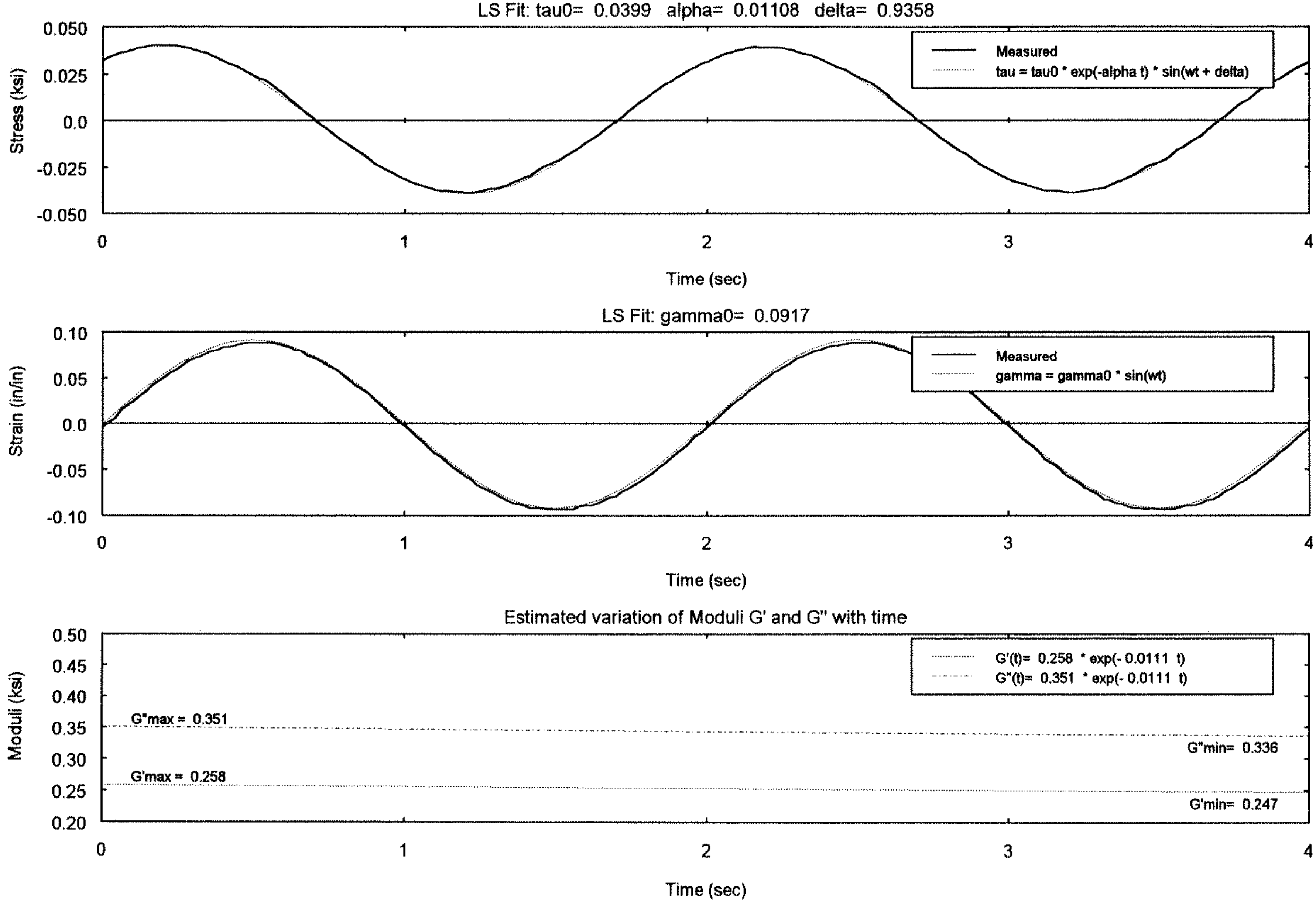
Test date: June 11, 1993 File: d1h301a.txt





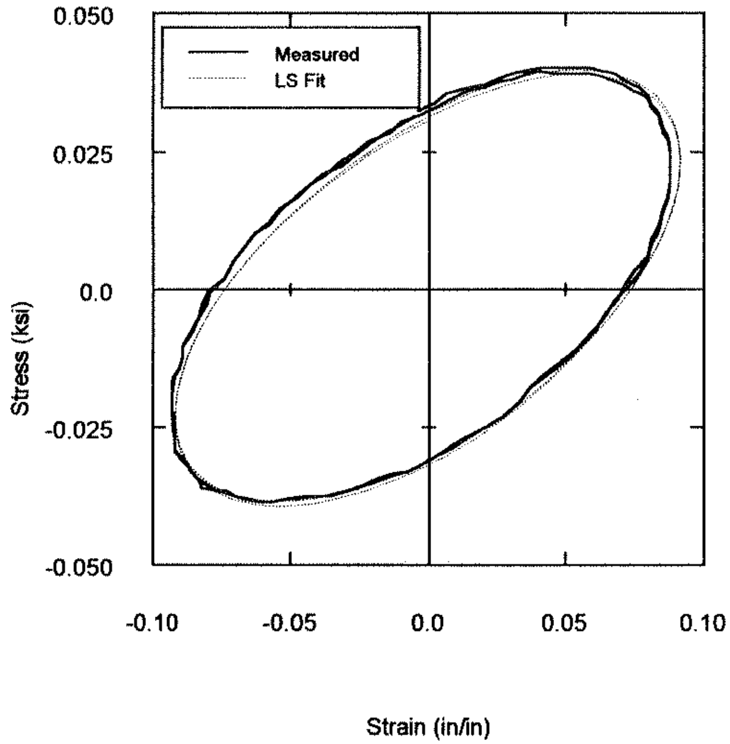
Damper No. 1 Harmonic 3 Cycle 2nd Test - Dmax = 0.1"

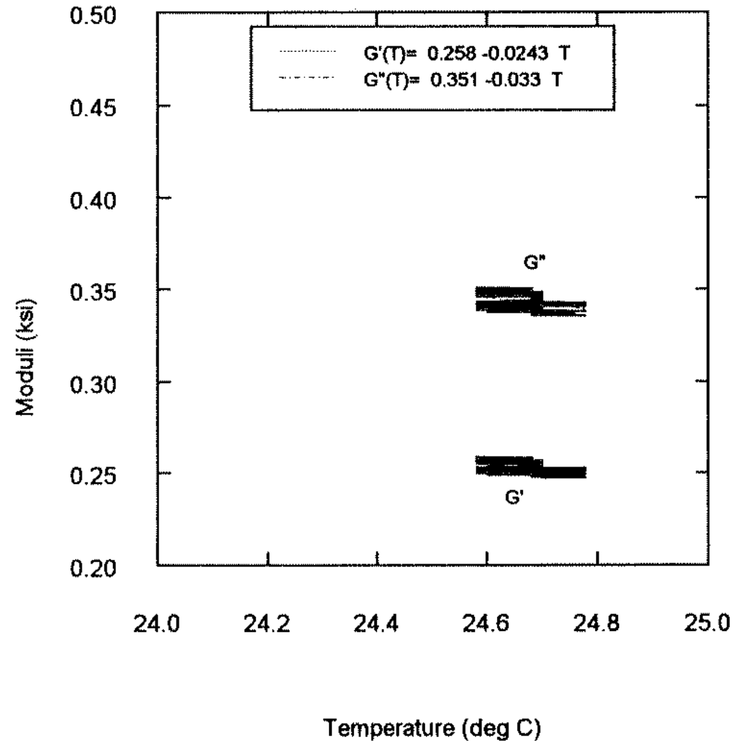
Test date: June 11, 1993 File: d1h301a.txt



Damper No. 1   Harmonic 3 Cycle 2nd Test - Dmax = 0.1"

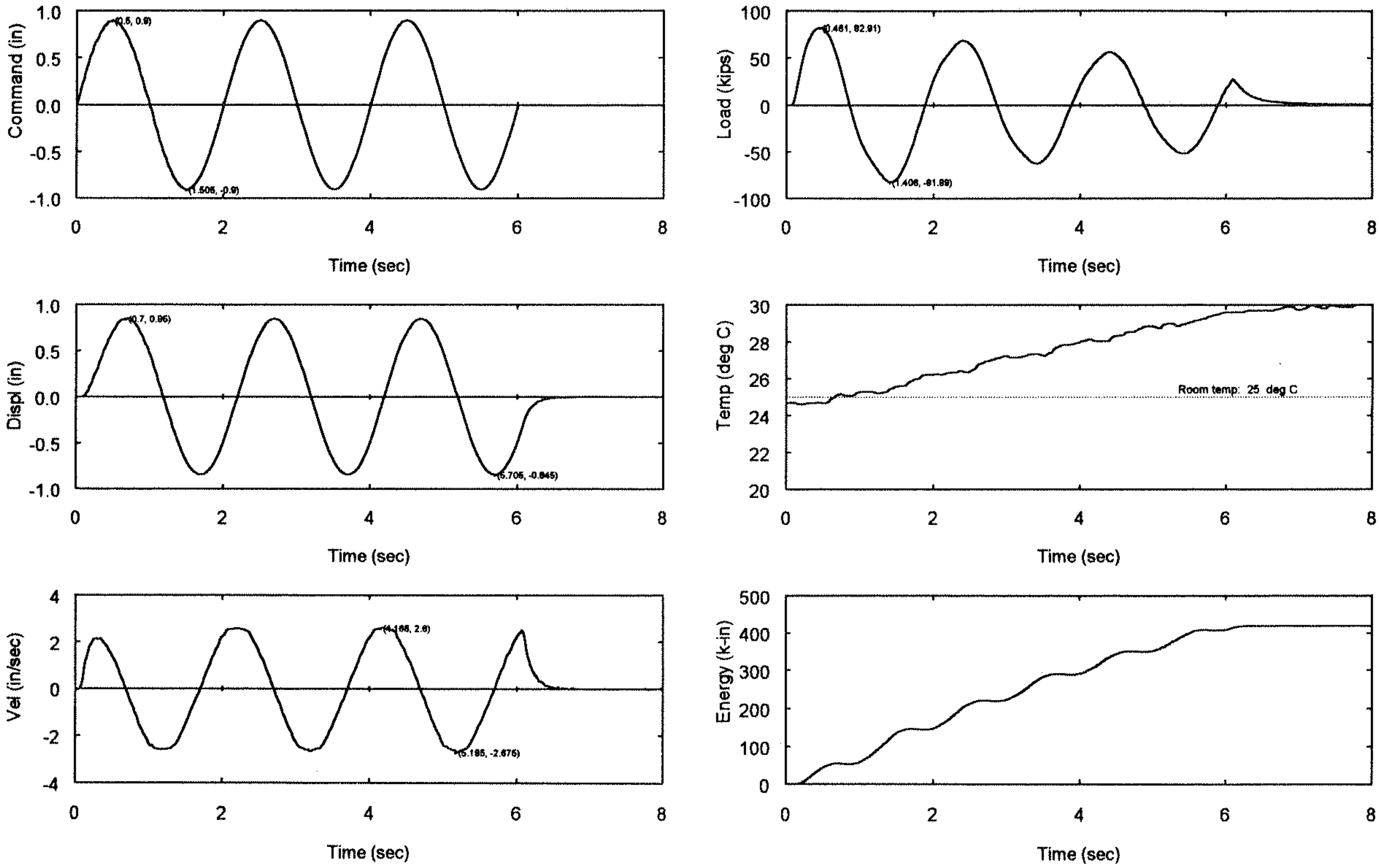
Test date: June 11, 1993   File: d1h301a.txt





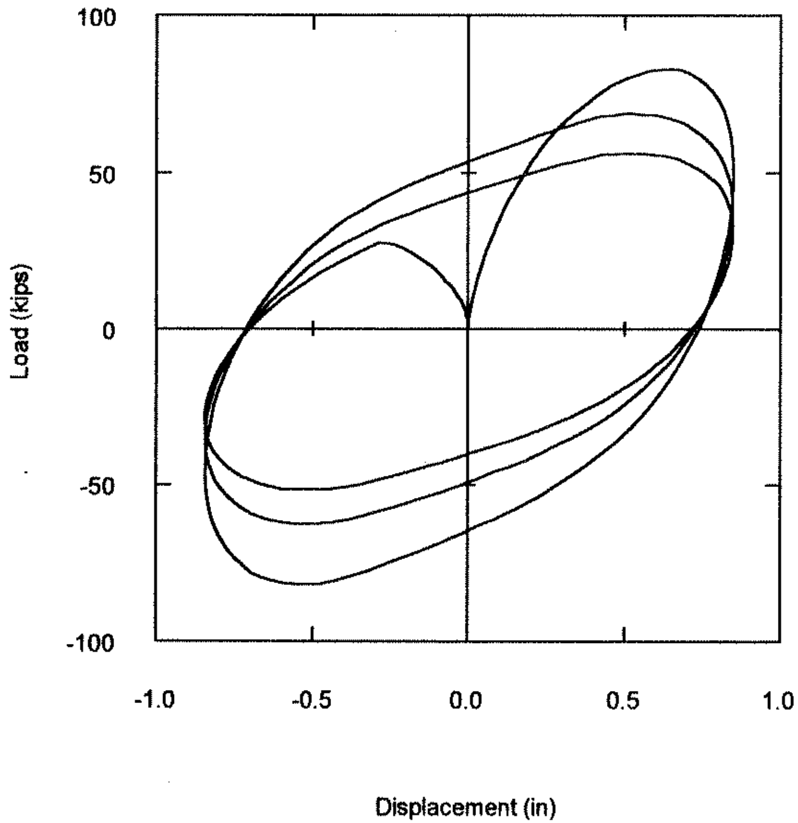
Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.9"

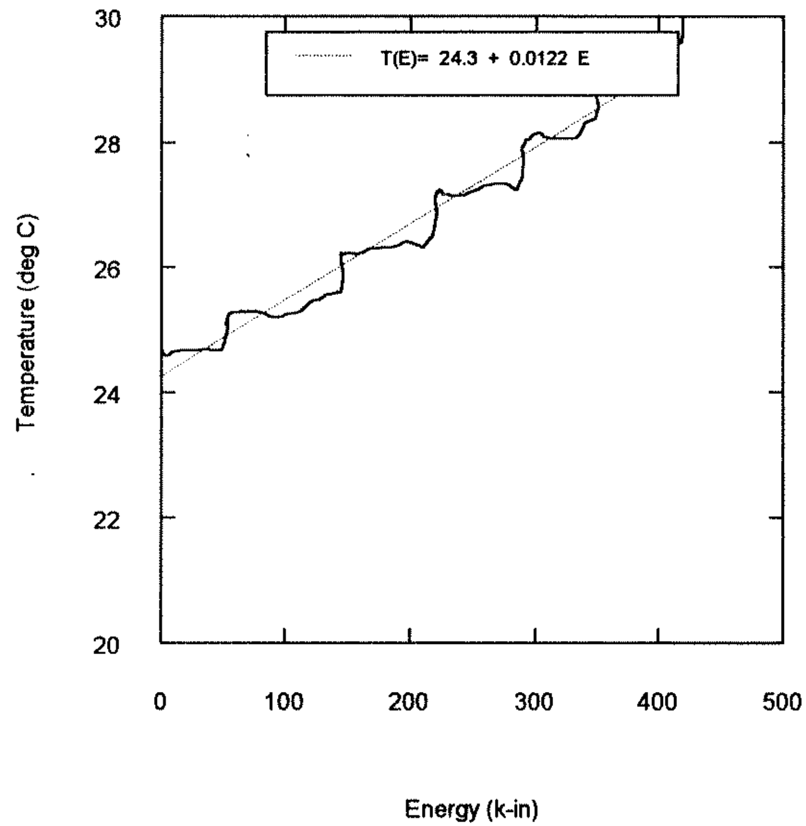
Test date: June 11, 1993 File: d1h309.txt



Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.9"

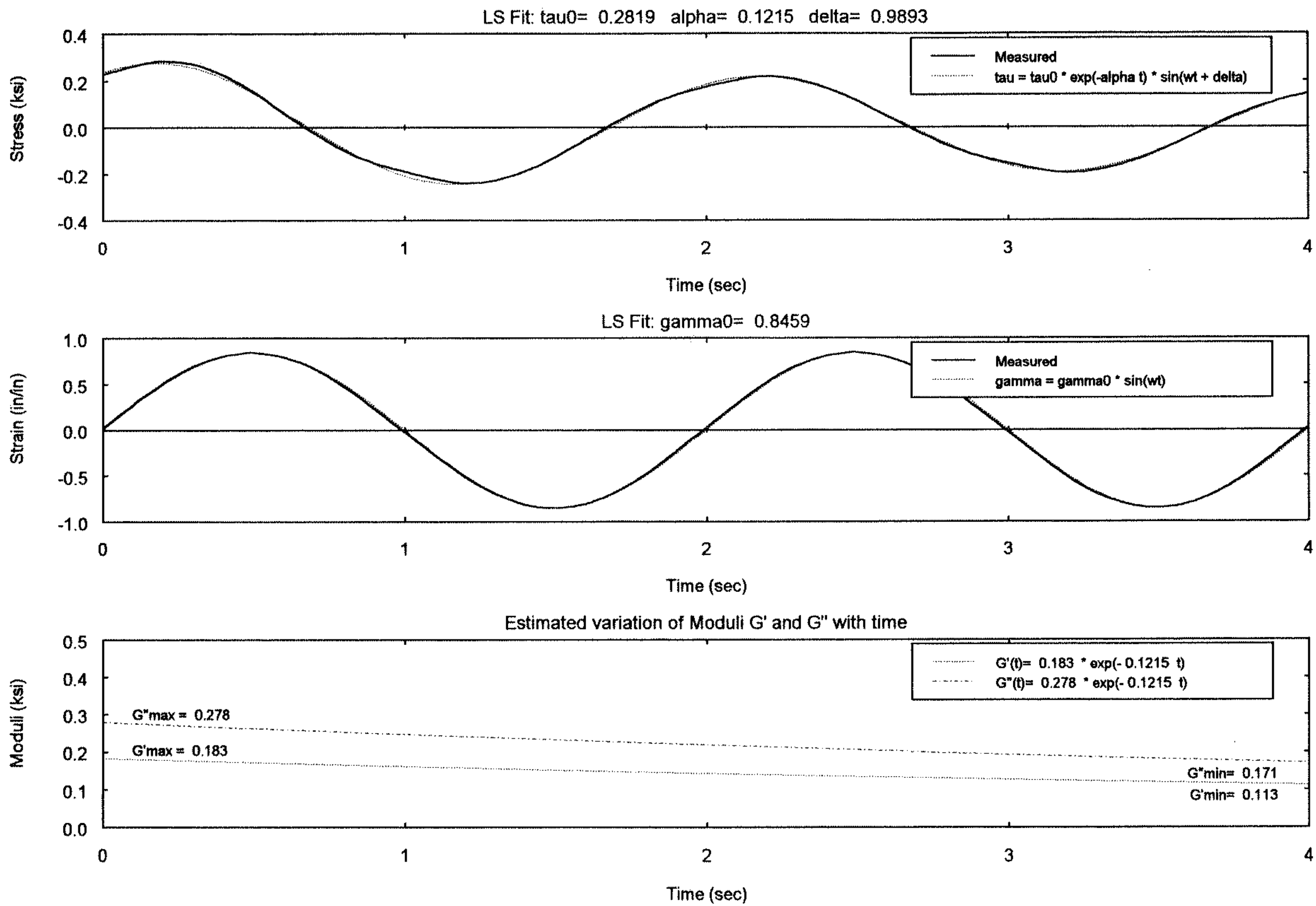
Test date: June 11, 1993 File: d1h309.txt





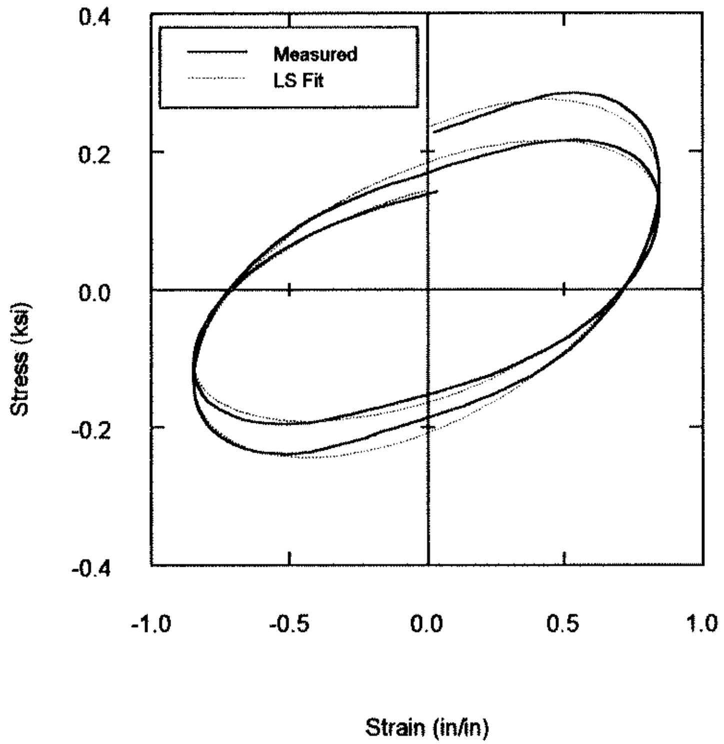
Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.9"

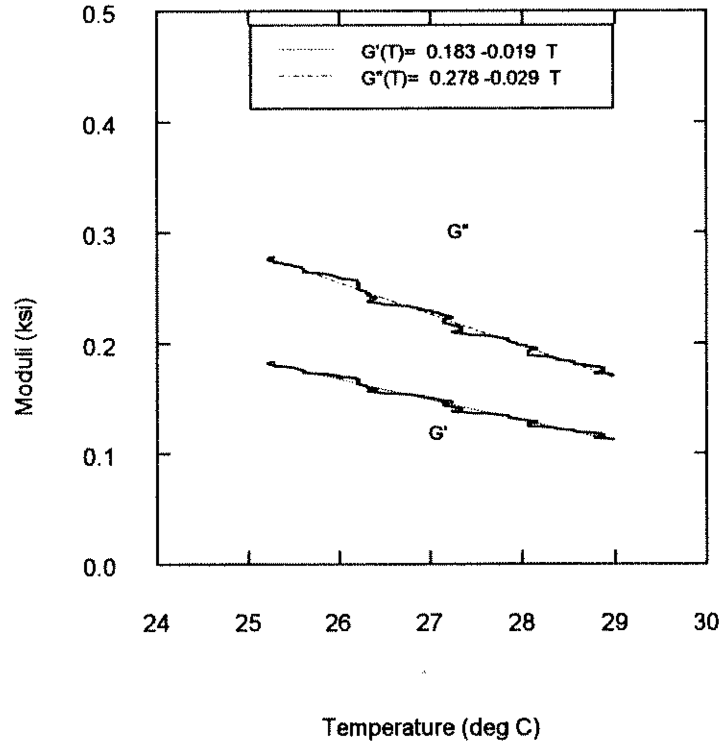
Test date: June 11, 1993 File: d1h309.txt



Damper No. 1 Harmonic 3 Cycle Test - Dmax = 0.9"

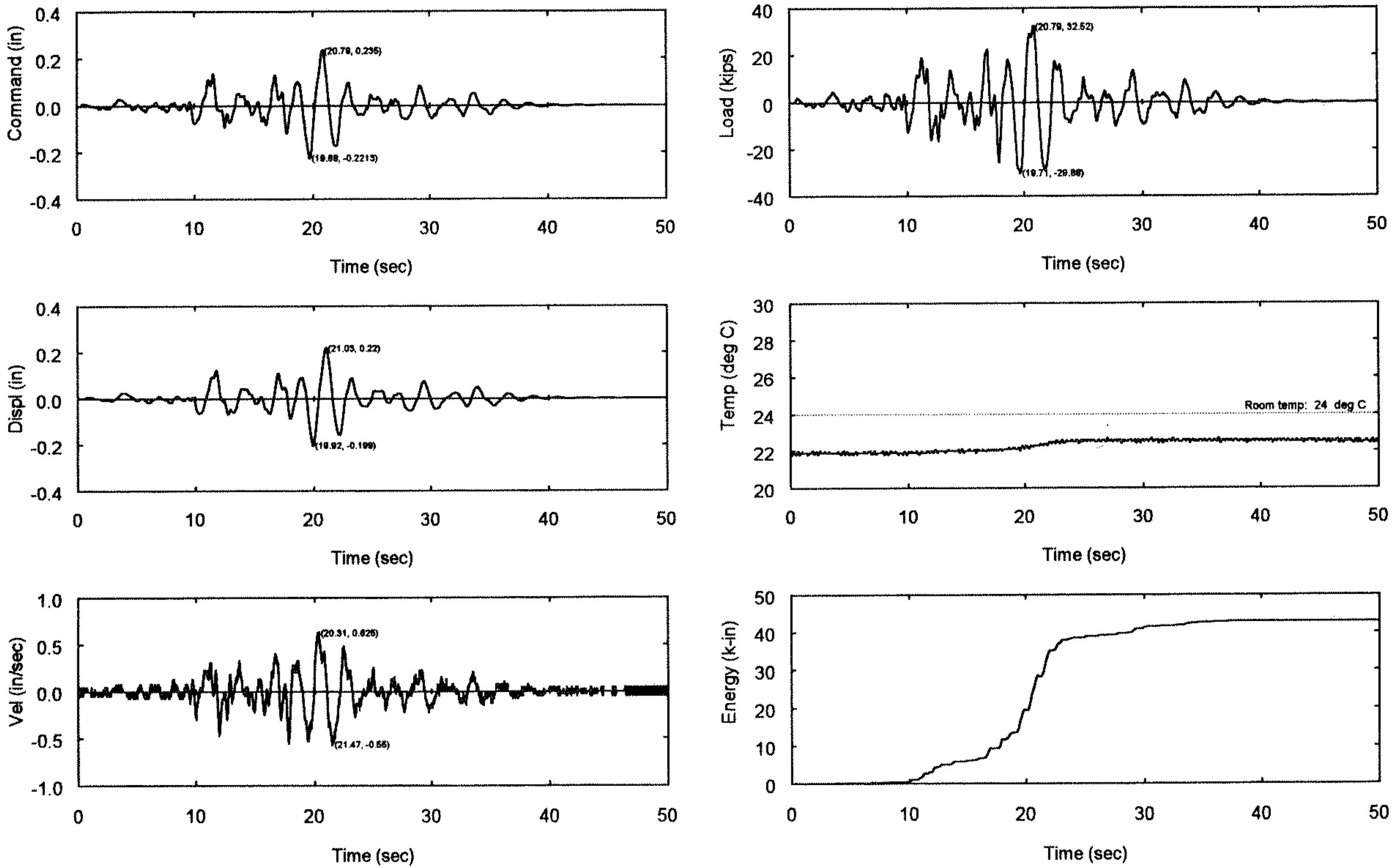
Test date: June 11, 1993 File: d1h309.txt





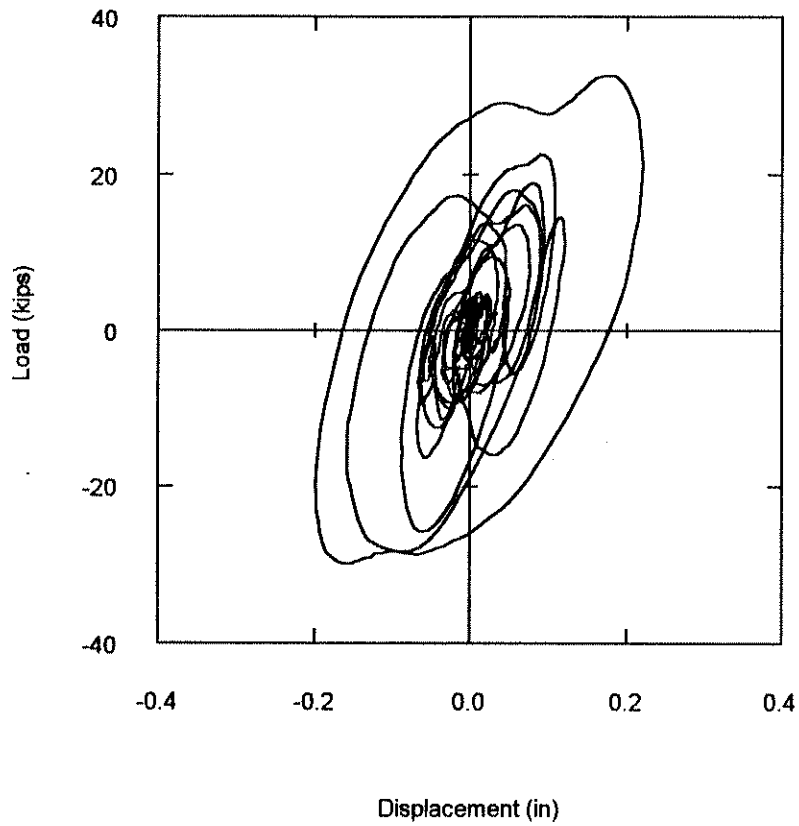
Damper No. 2 Earthquake Test - Dmax = 0.235"

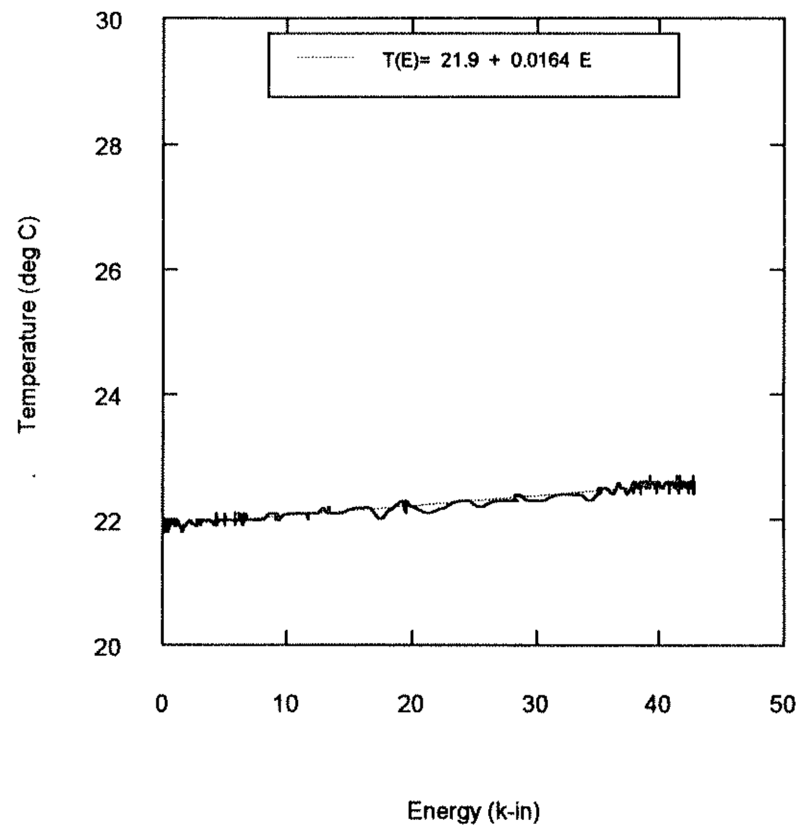
Test date: June 10, 1993 File: d2eq02.txt



Damper No. 2 Earthquake Test - Dmax = 0.235"

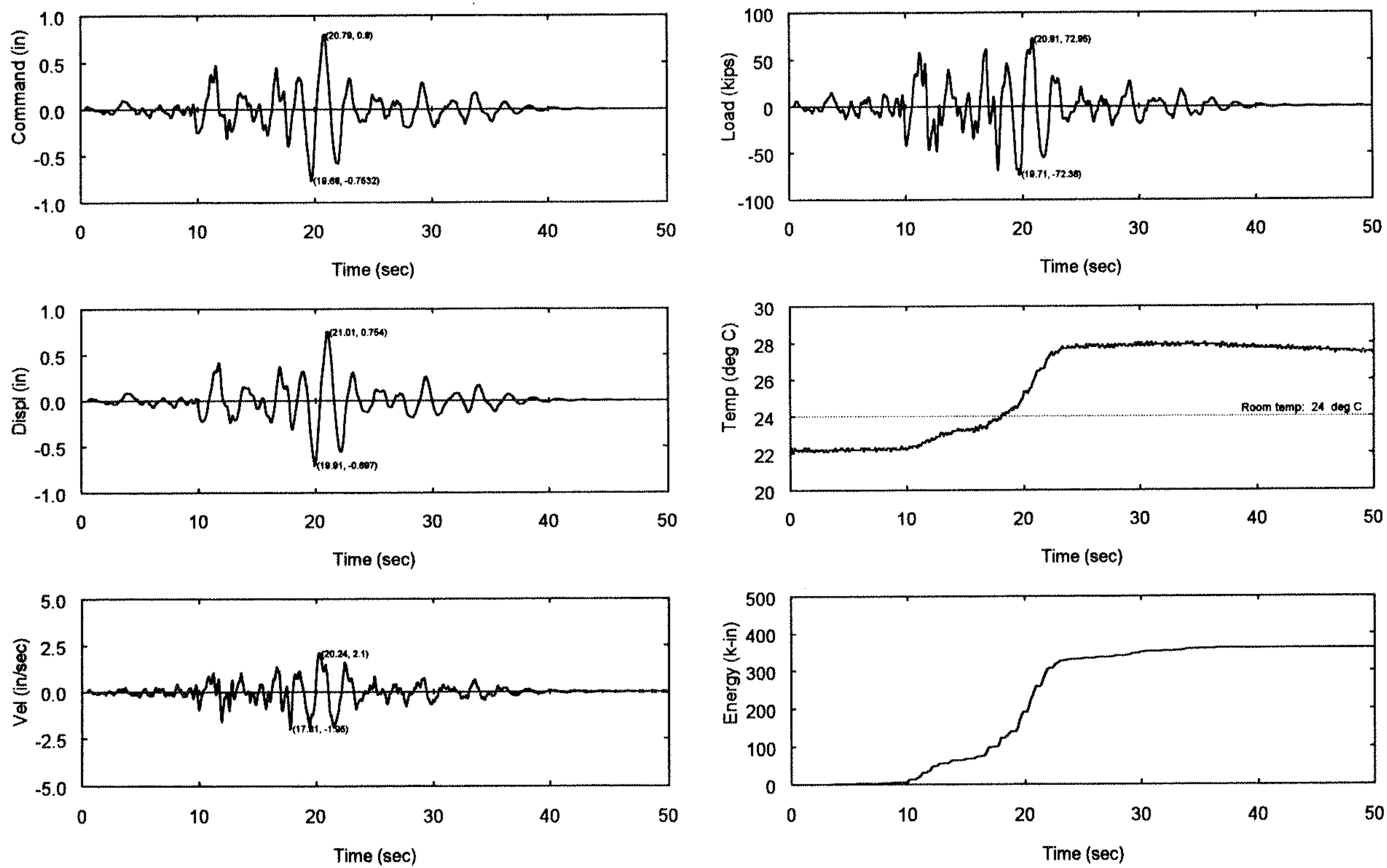
Test date: June 10, 1993 File: d2eq02.txt





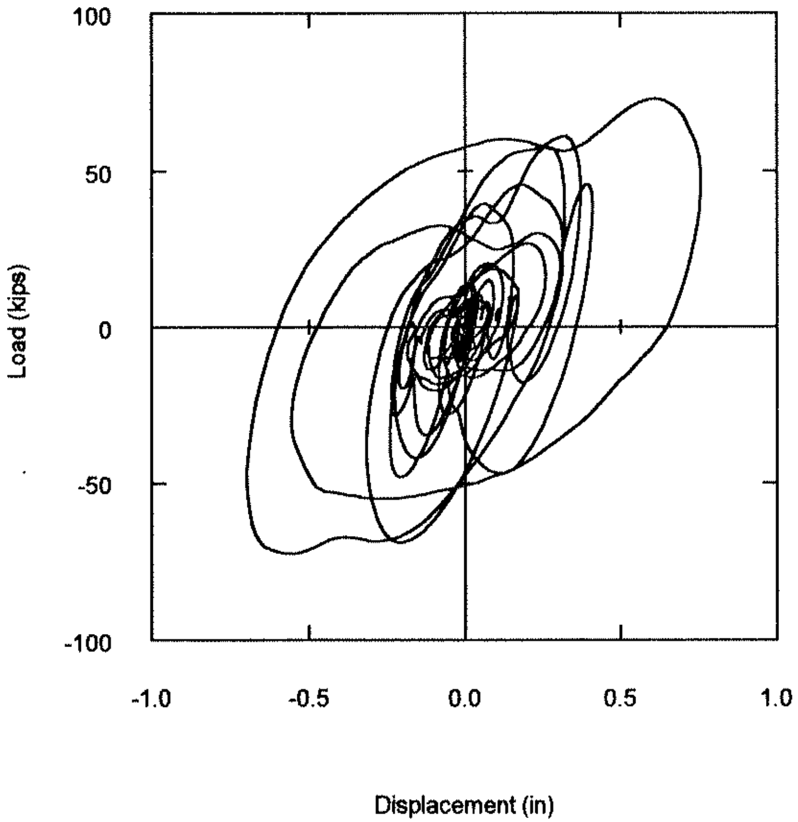
Damper No. 2 Earthquake Test - Dmax = 0.8"

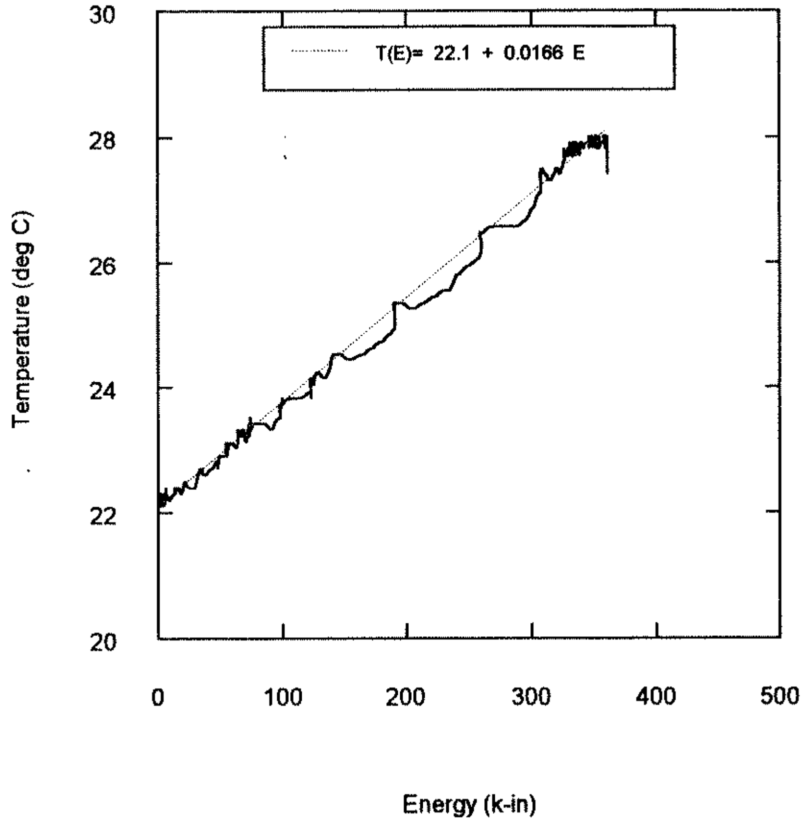
Test date: June 10, 1993 File: d2eq08.txt



Damper No. 2 Earthquake Test - Dmax = 0.8"

Test date: June 10, 1993 File: d2eq08.txt





Damper No. 2 Earthquake Test - Dmax = 1.0"

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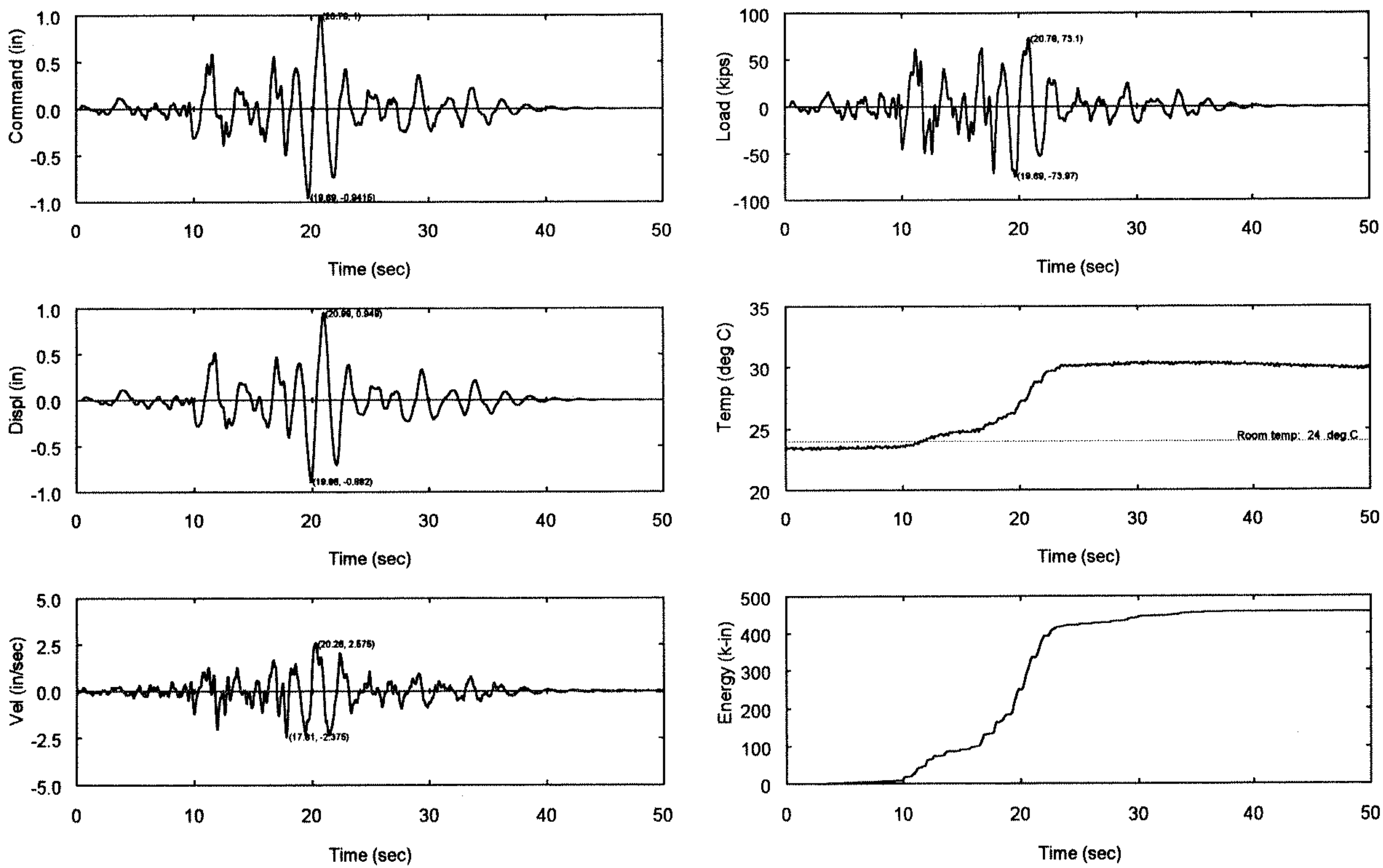
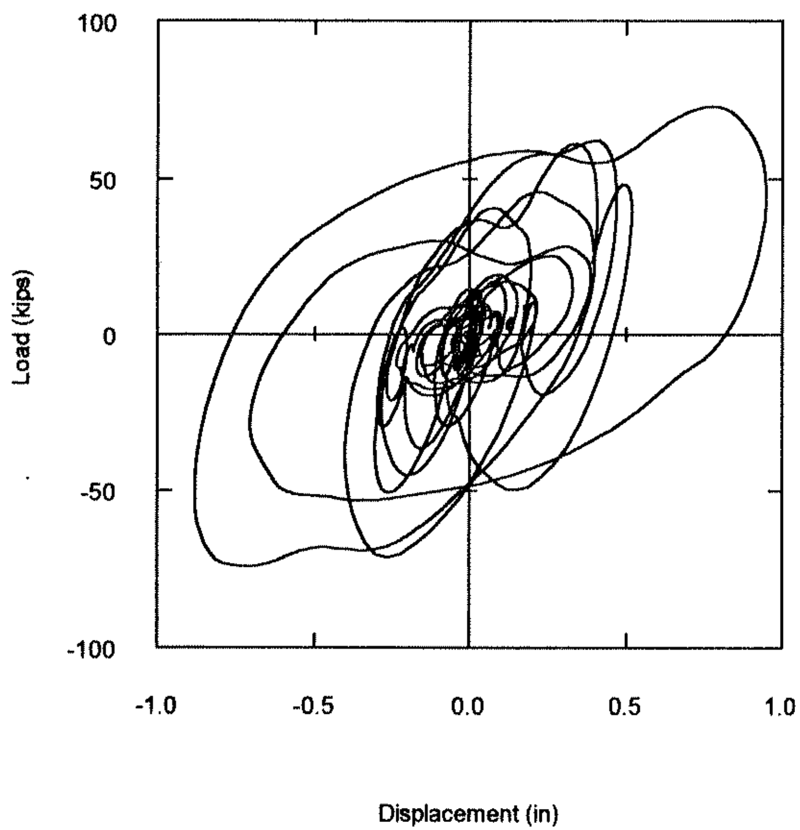
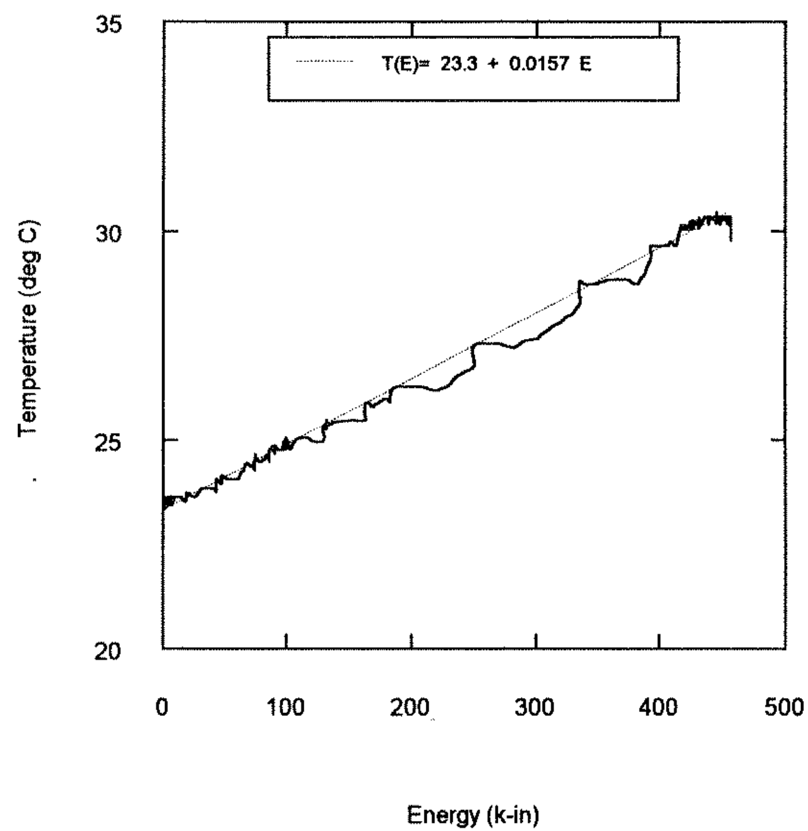


Damper No. 2 Earthquake Test - Dmax = 1.0"

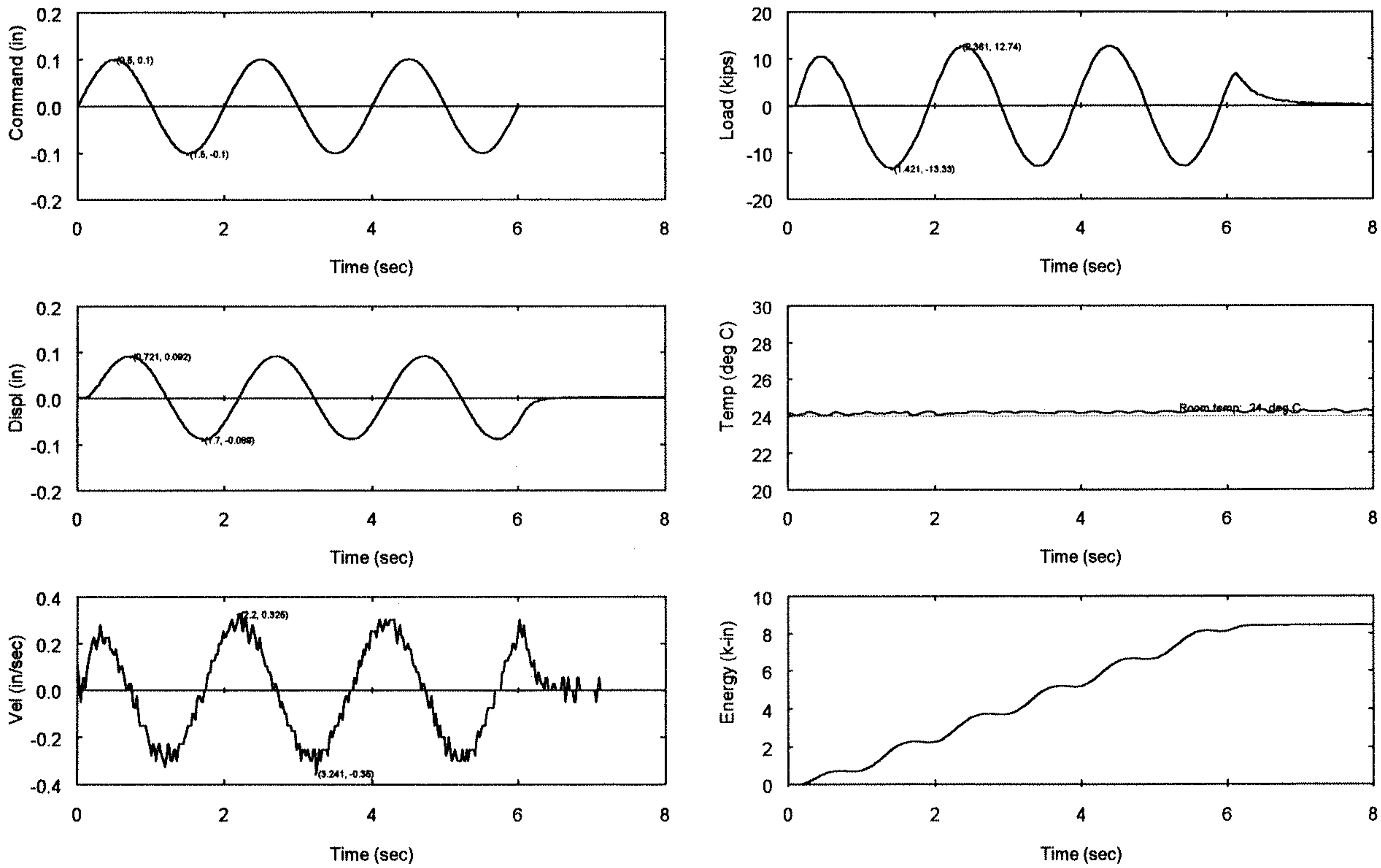
Test date: June 10, 1993 File: d2eq10.txt





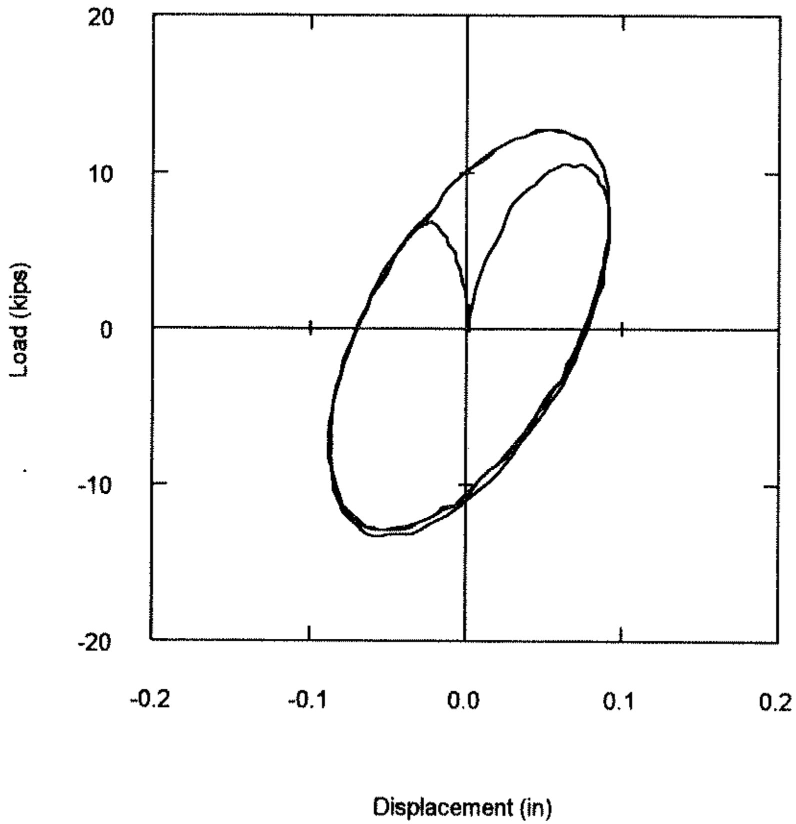
Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.1"

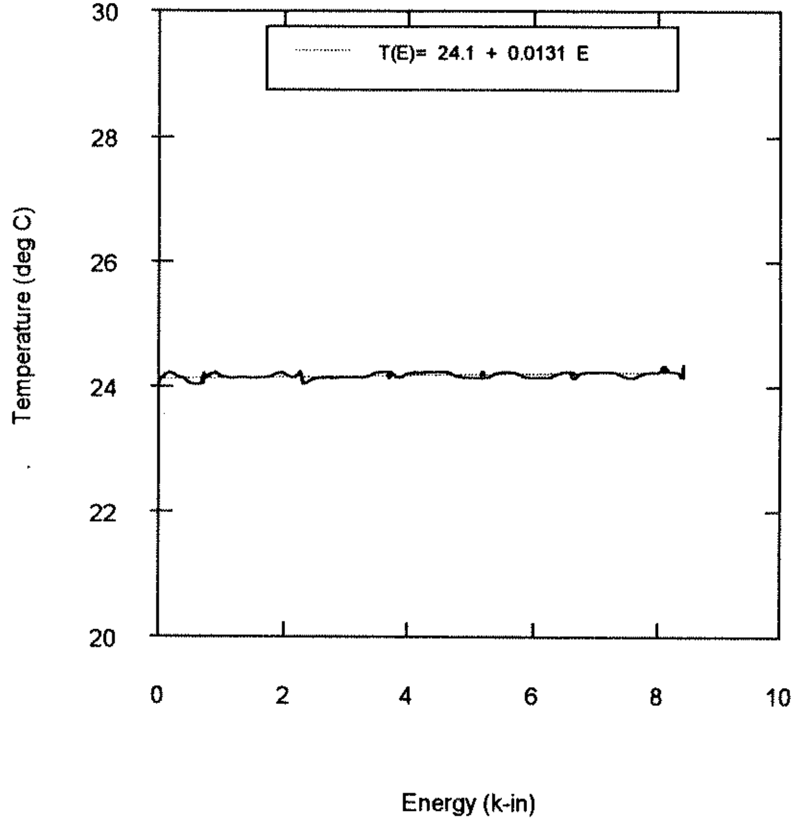
Test date: June 10, 1993 File: d2h301.txt



Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.1"

Test date: June 10, 1993 File: d2h301.txt





Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.1"

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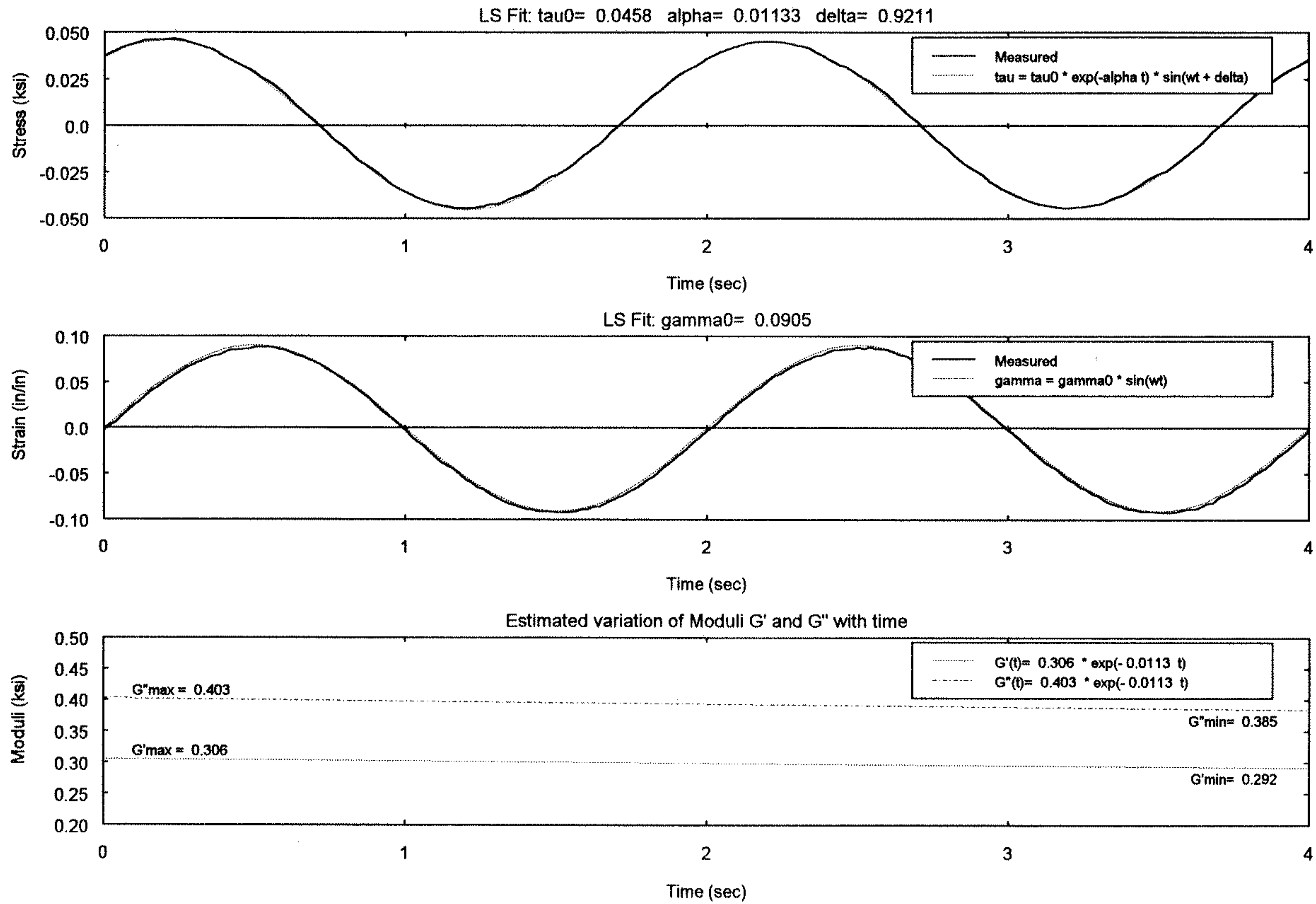
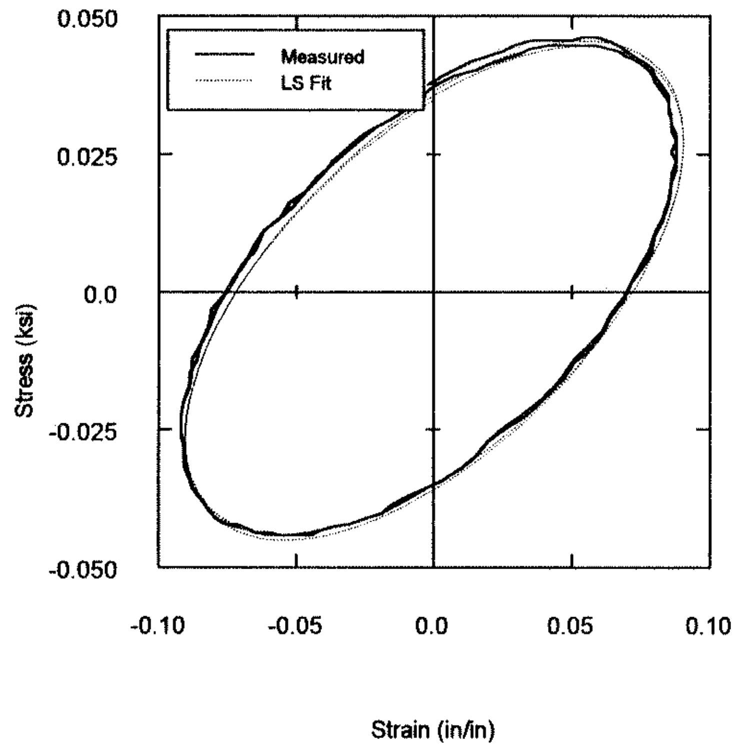
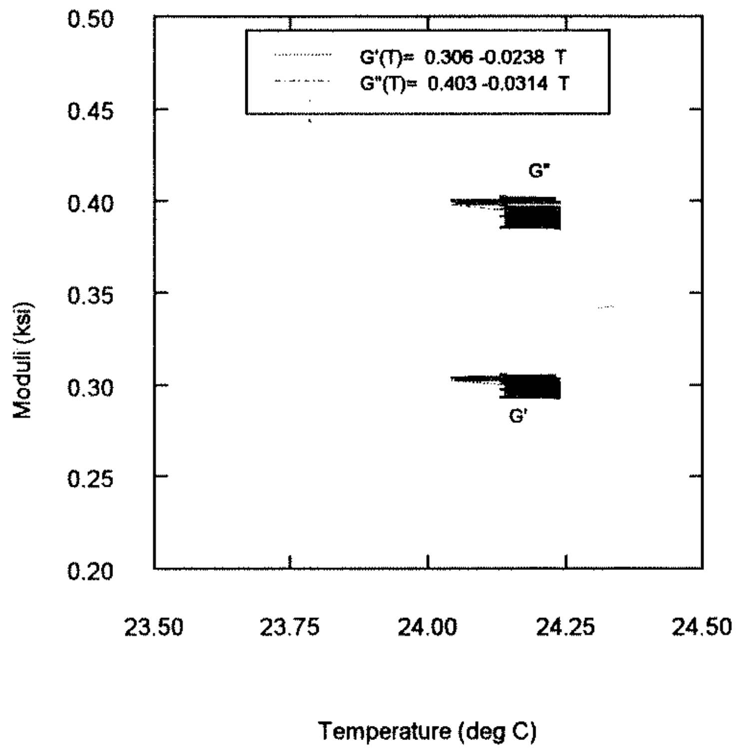


Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.1"

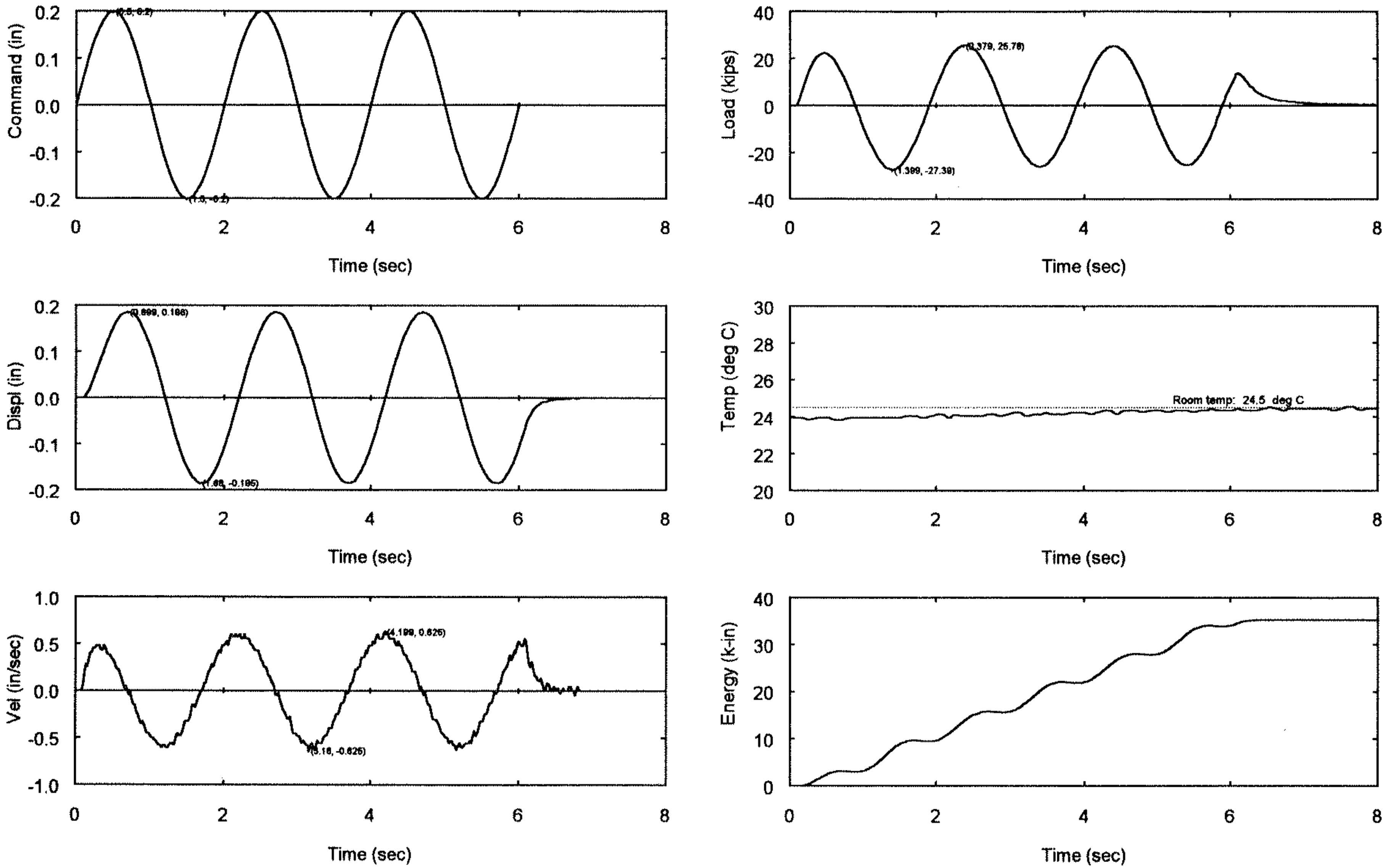
Test date: June 10, 1993 File: d2h301.txt





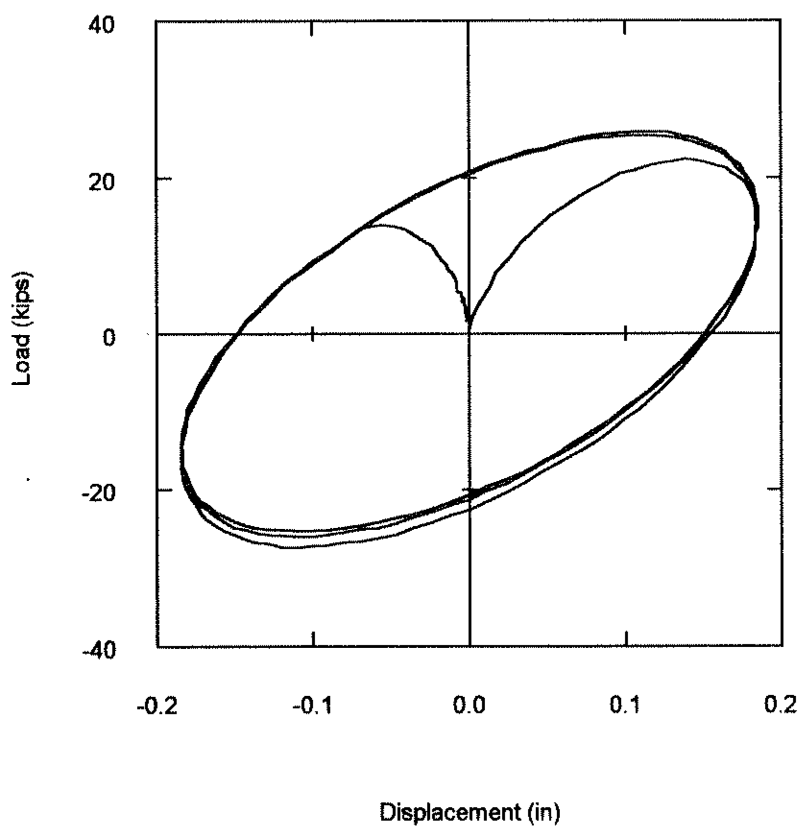
Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.2"

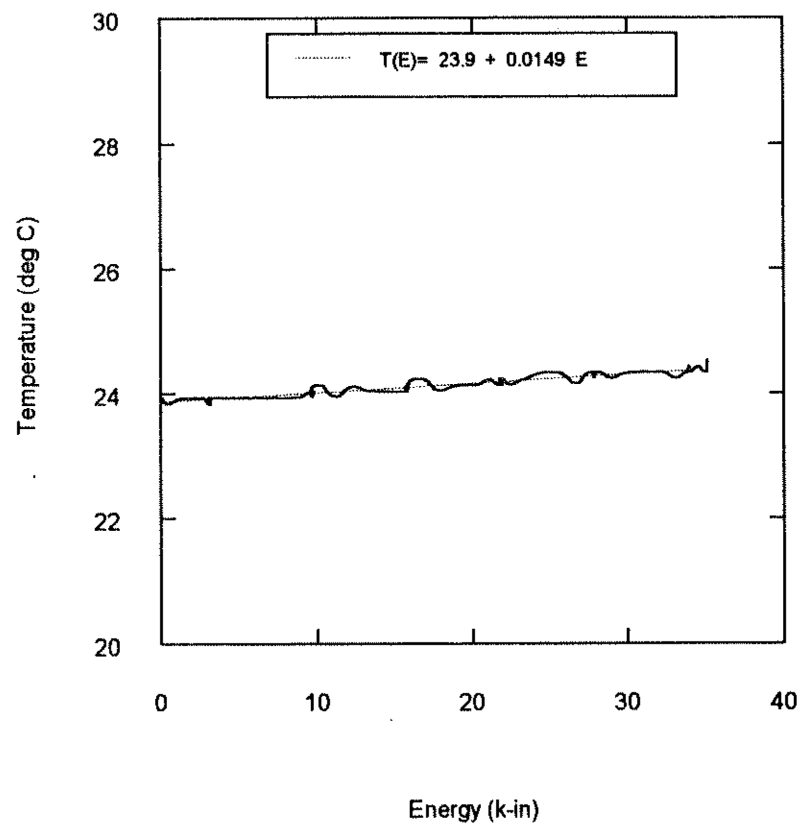
Test date: June 10, 1993 File: d2h302.txt



Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.2"

Test date: June 10, 1993 File: d2h302.txt





Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.2"

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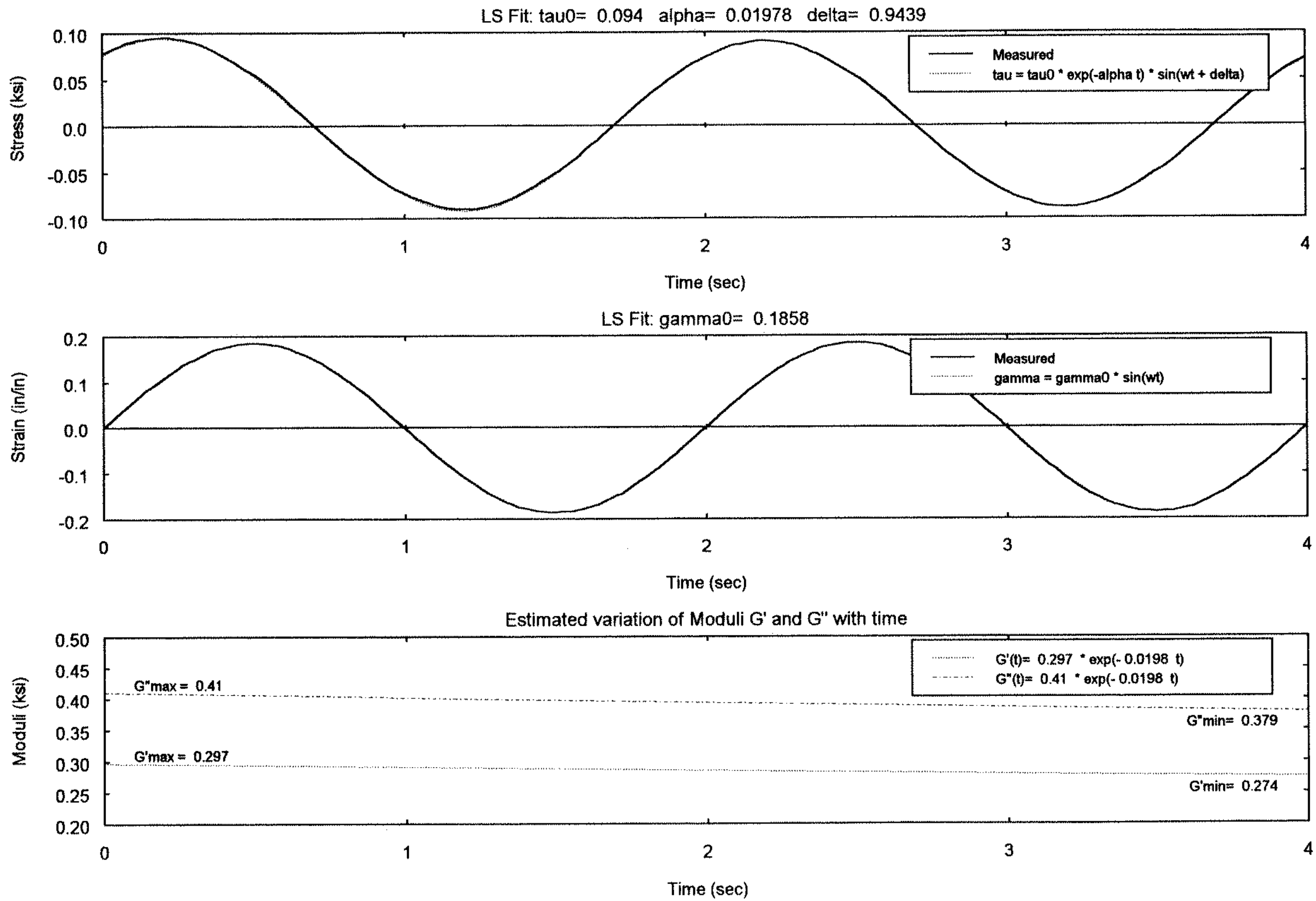

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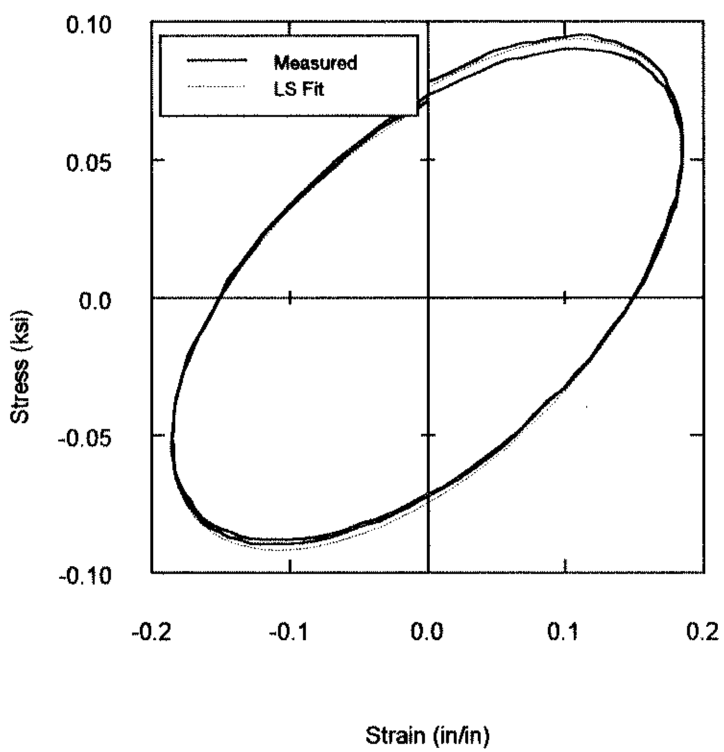
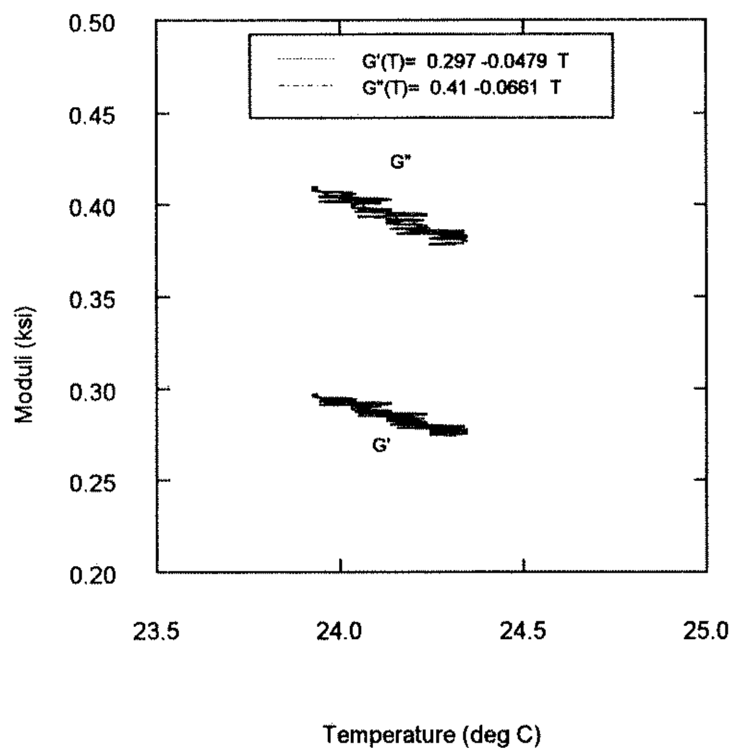
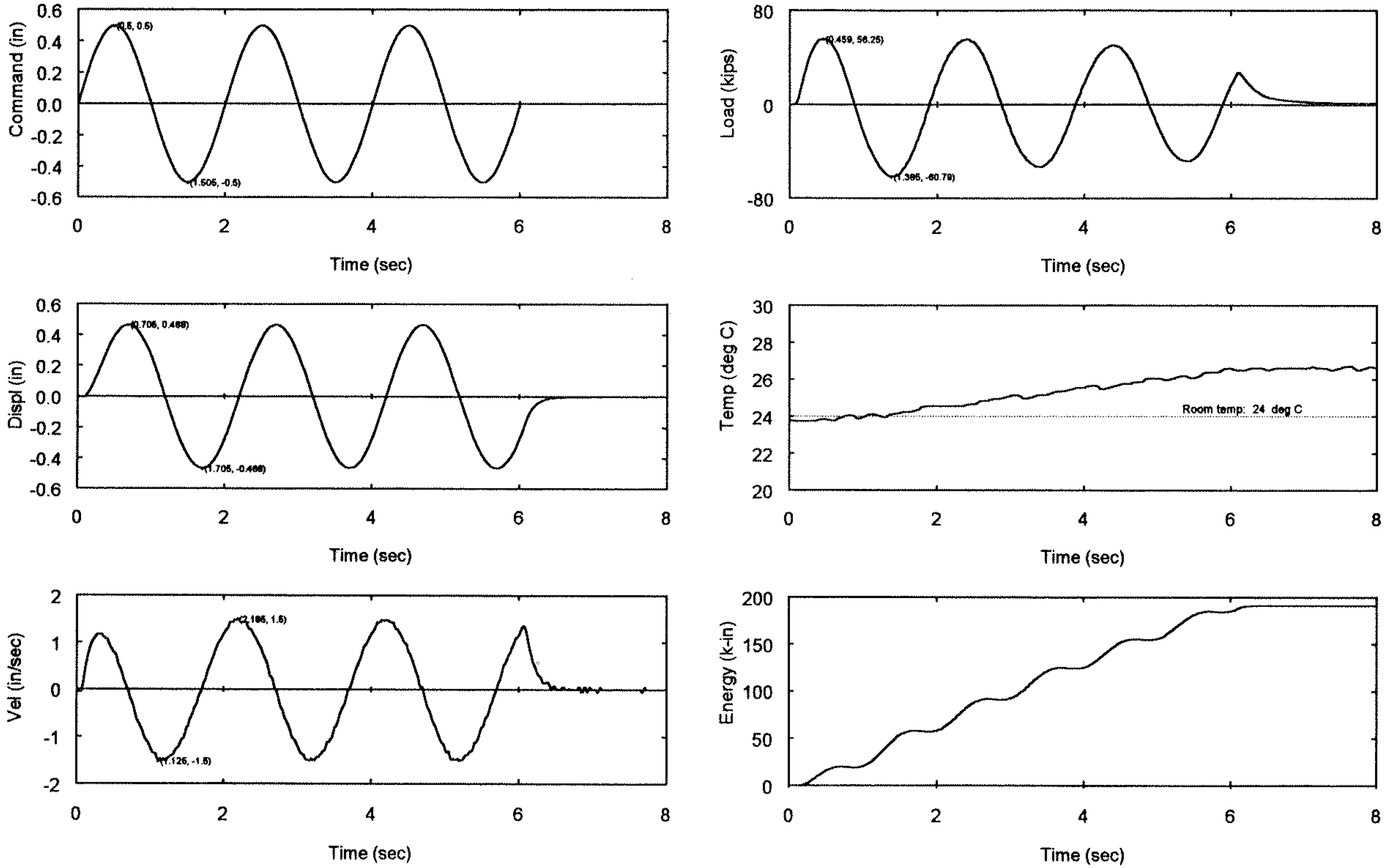




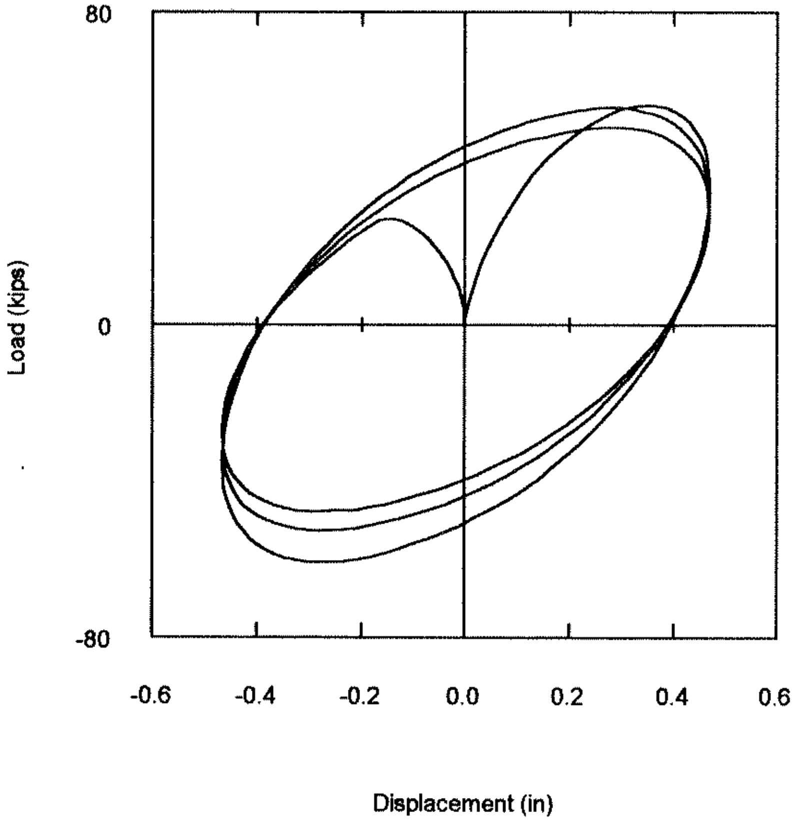
Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.5"

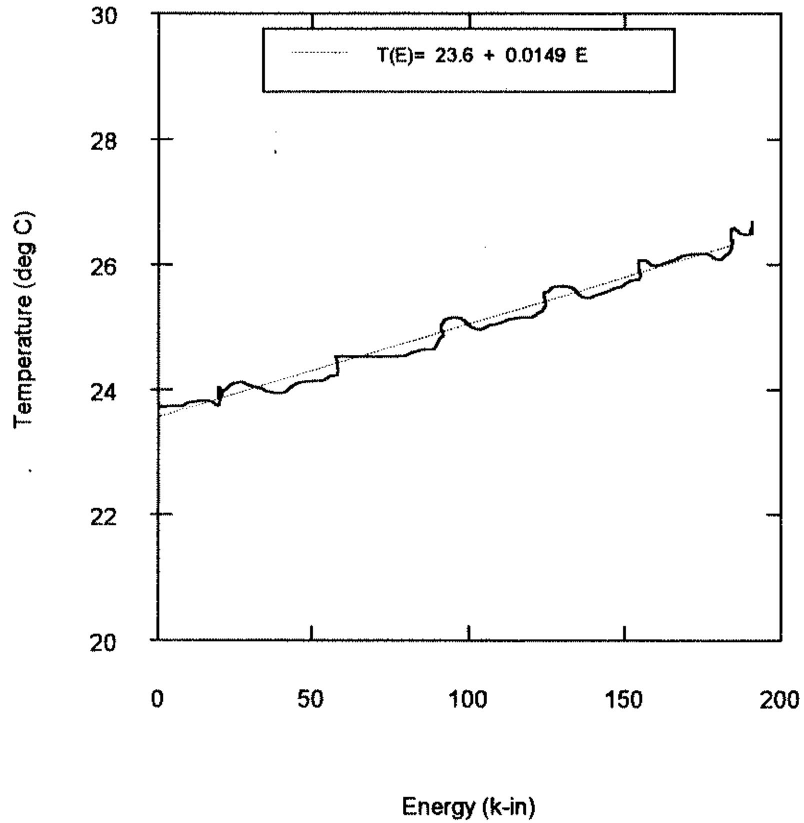
Test date: June 10, 1993 File: d2h305.txt



Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.5"

Test date: June 10, 1993 File: d2h305.txt

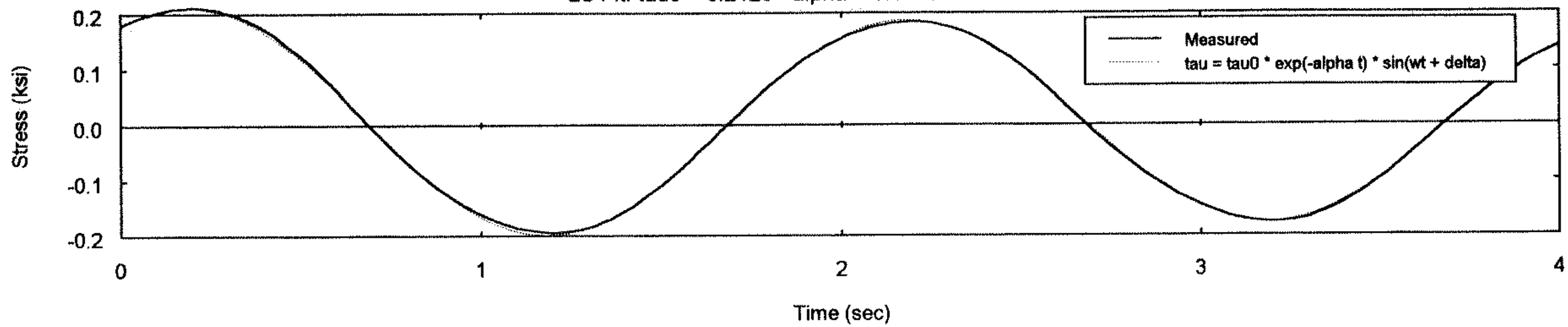




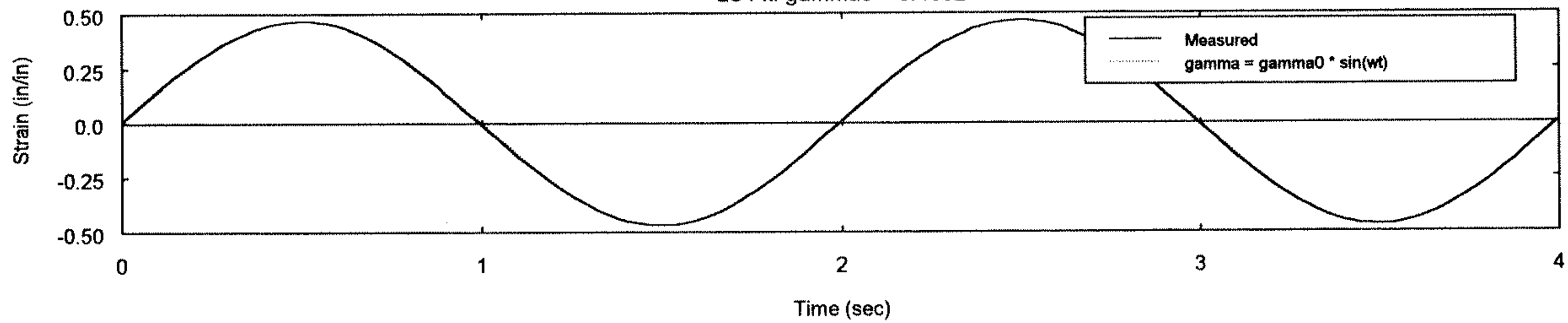
Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.5"

Test date: June 10, 1993 File: d2h305.txt

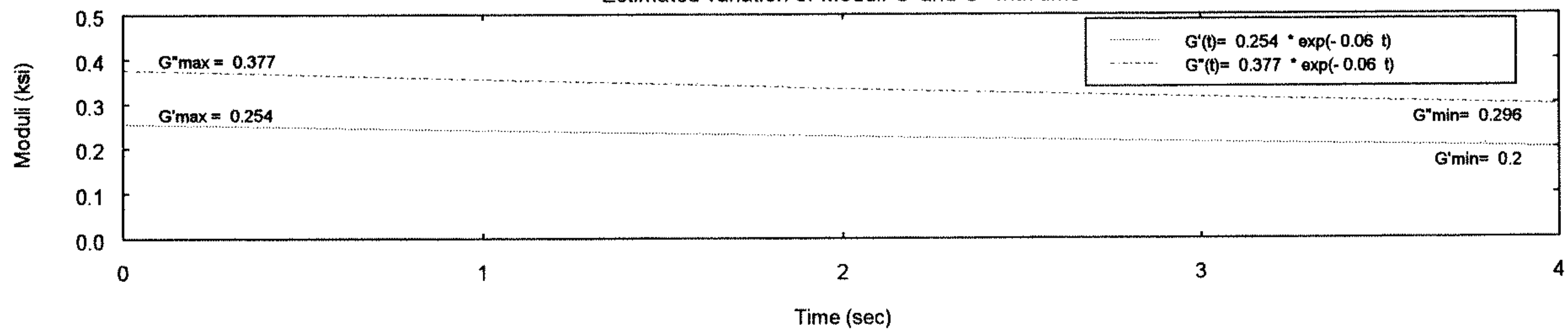
LS Fit: tau0= 0.2128 alpha= 0.06003 delta= 0.9767



LS Fit: gamma0= 0.4682

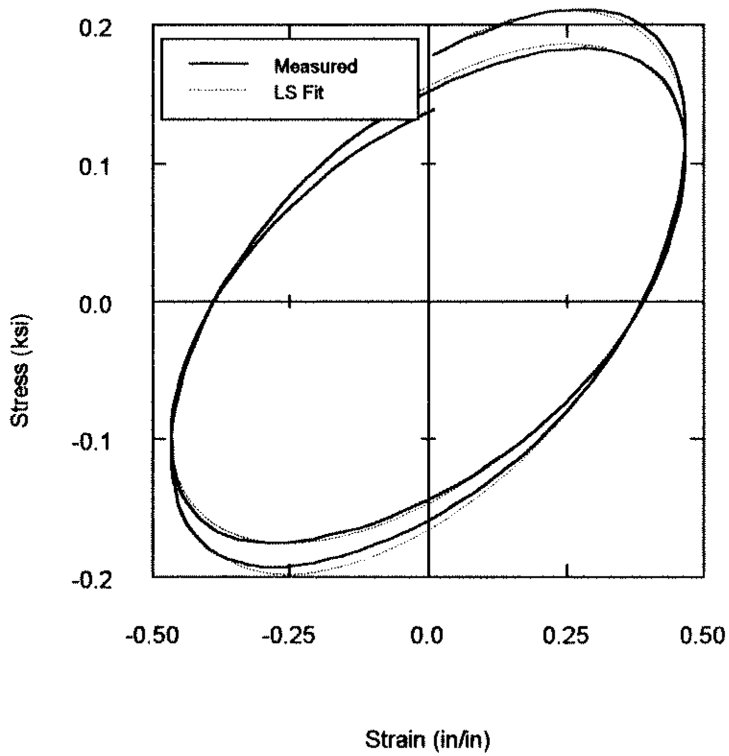


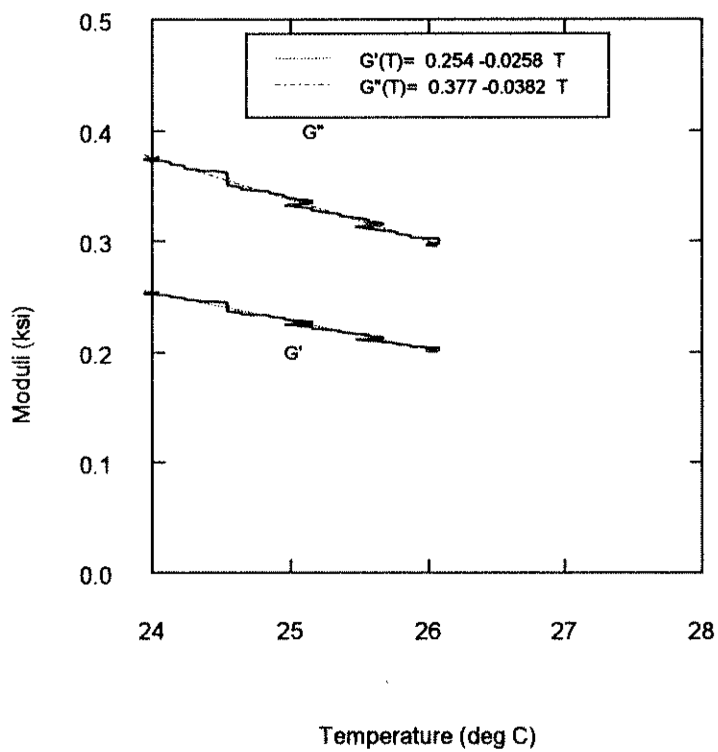
Estimated variation of Moduli G' and G" with time



Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.5"

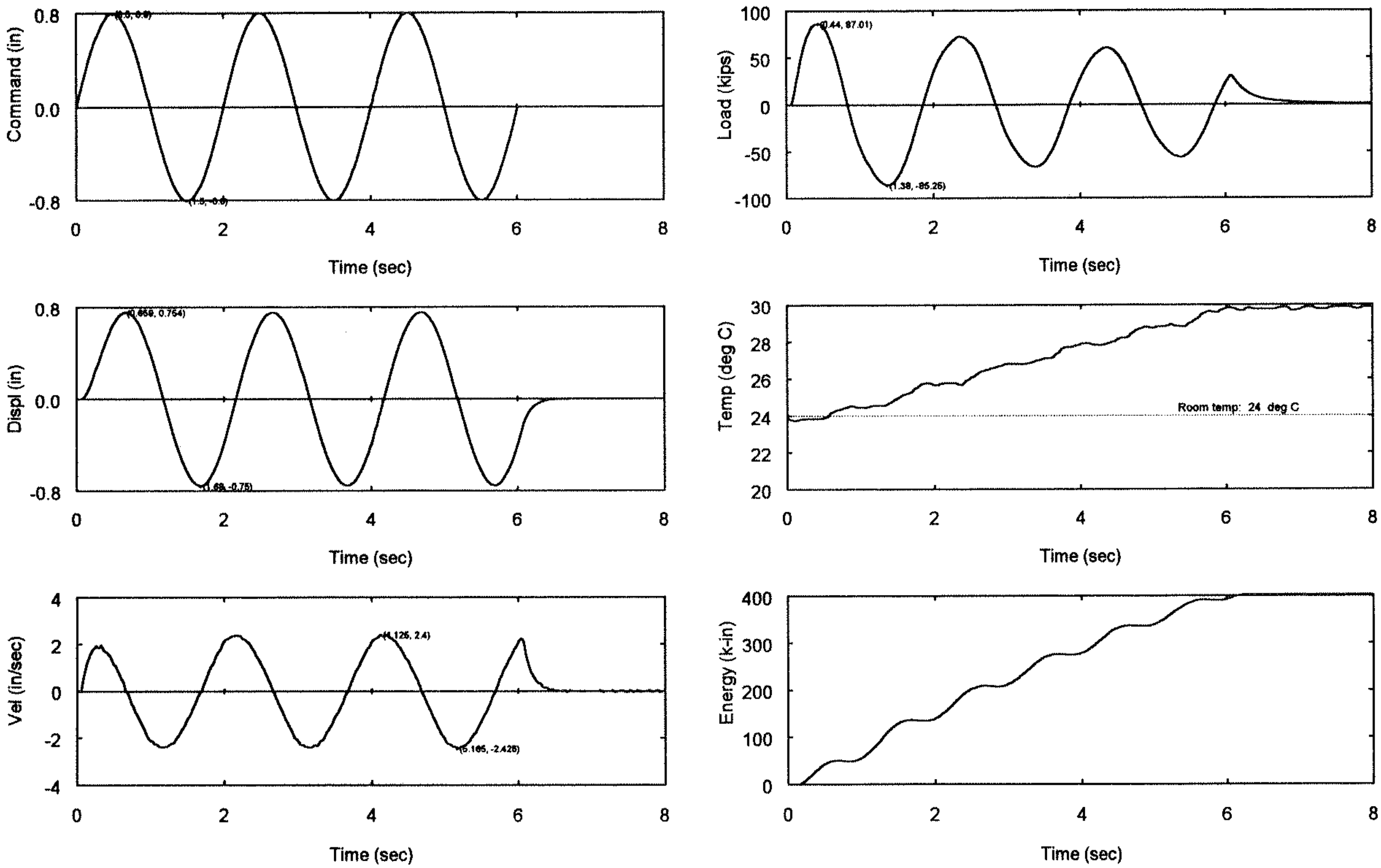
Test date: June 10, 1993 File: d2h305.txt





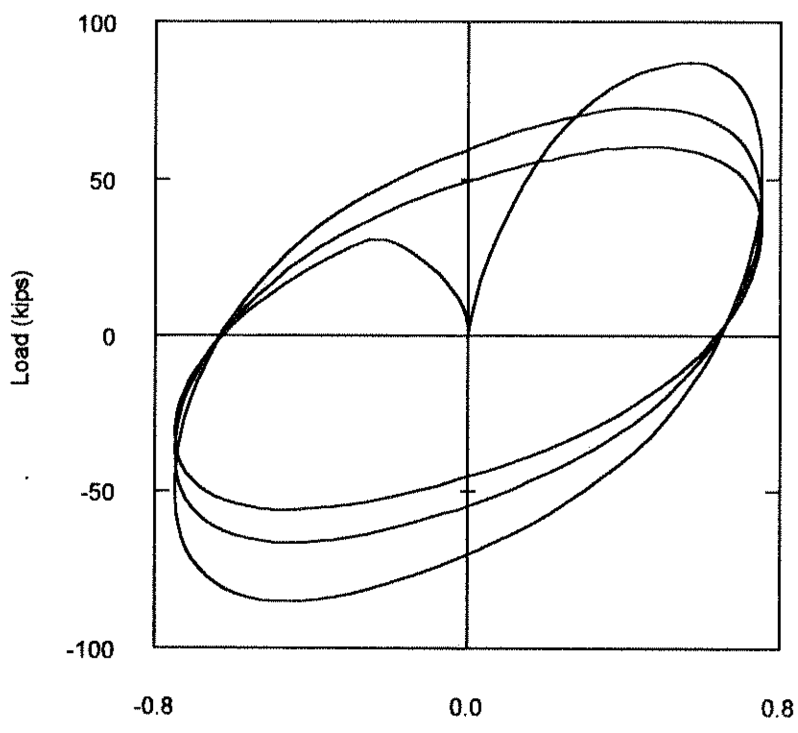
Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.8"

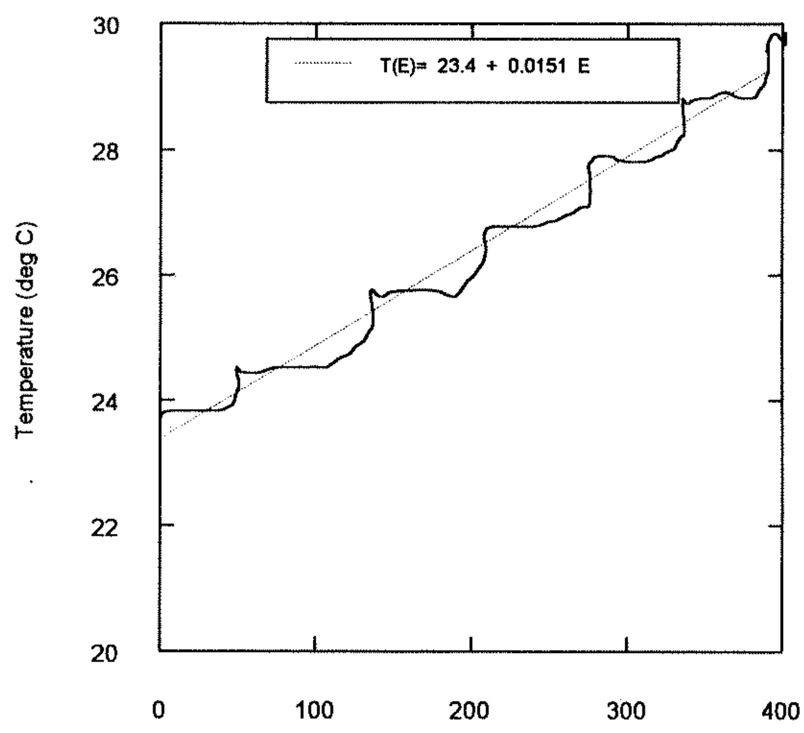
Test date: June 10, 1993 File: d2h308.txt



Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.8"

Test date: June 10, 1993 File: d2h308.txt

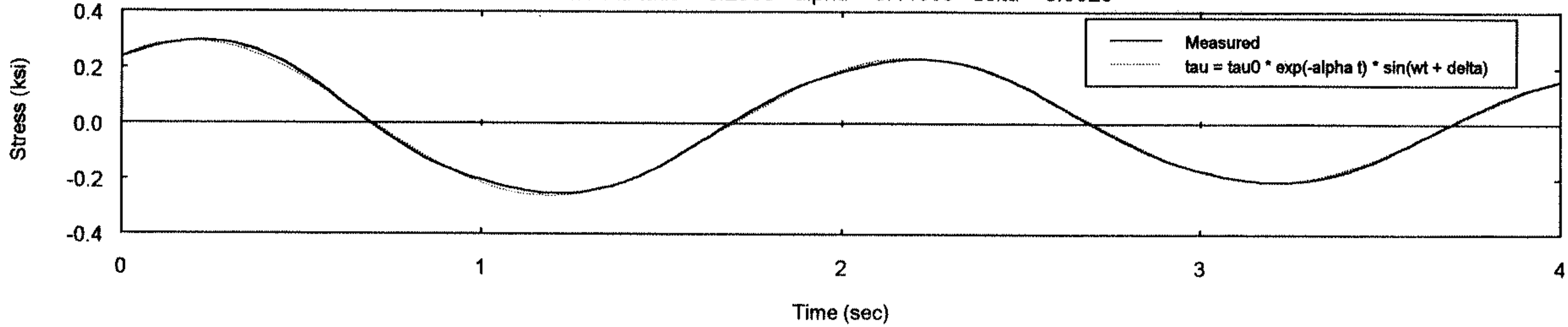




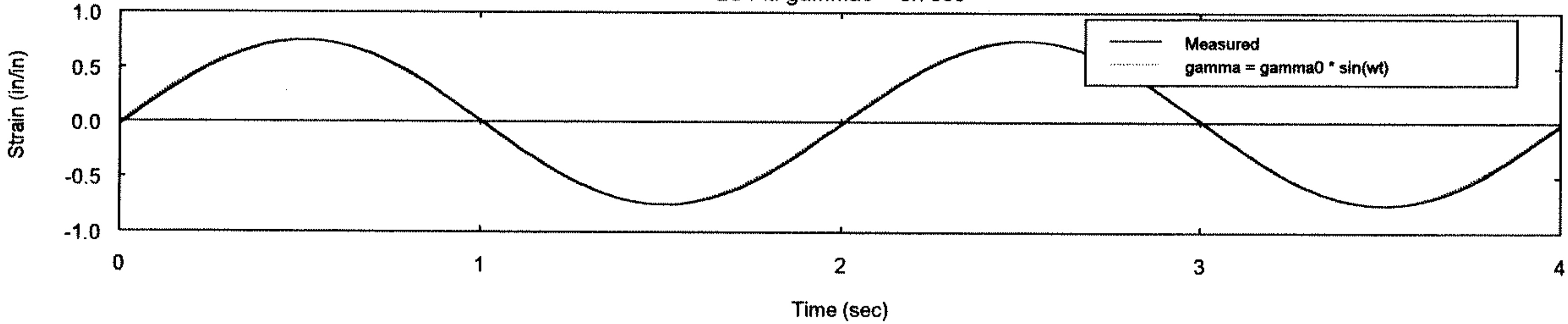
Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.8"

Test date: June 10, 1993 File: d2h308.txt

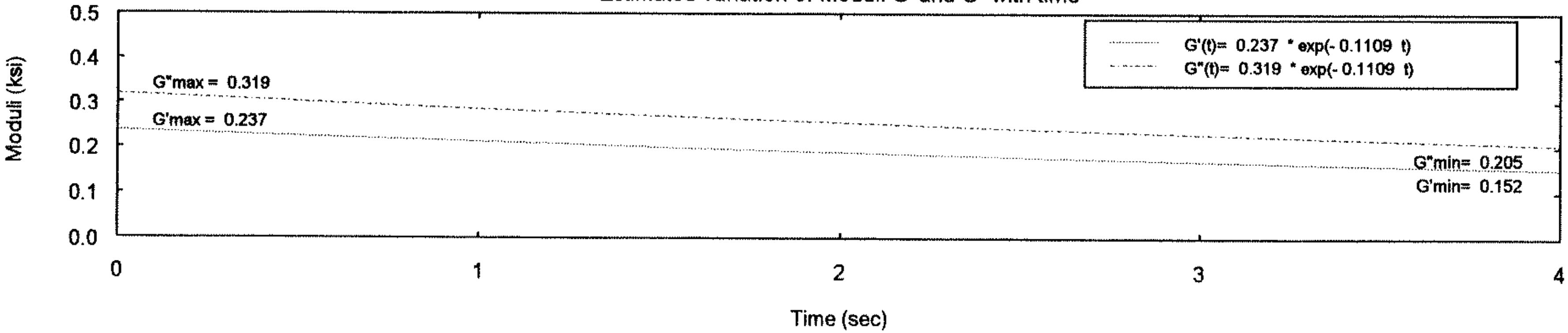
LS Fit: tau0= 0.2998 alpha= 0.11088 delta= 0.9326



LS Fit: gamma0= 0.7539

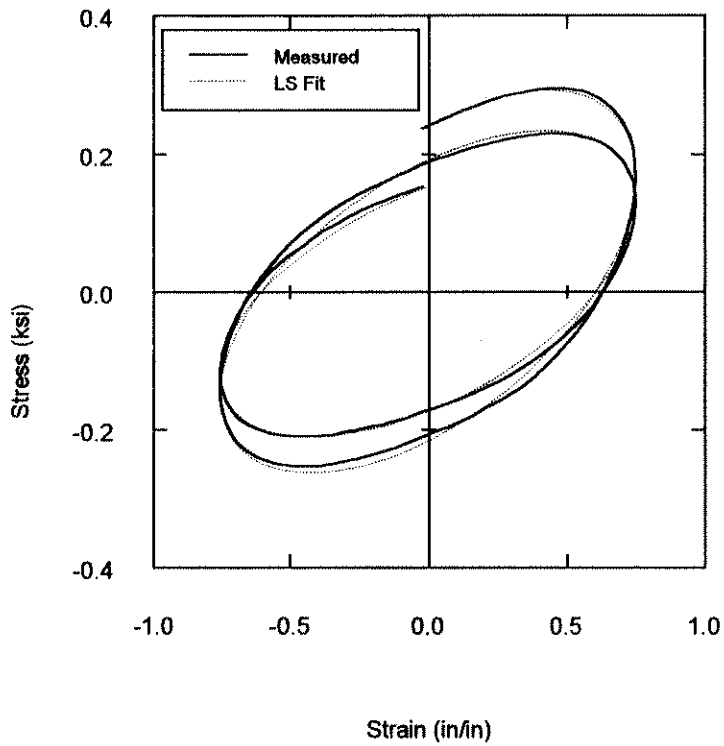


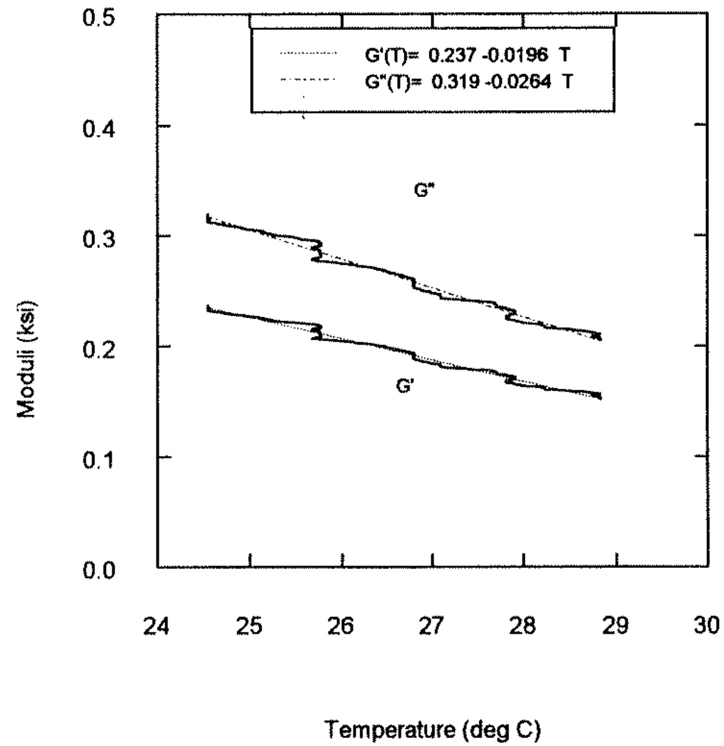
Estimated variation of Moduli G' and G" with time



Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.8"

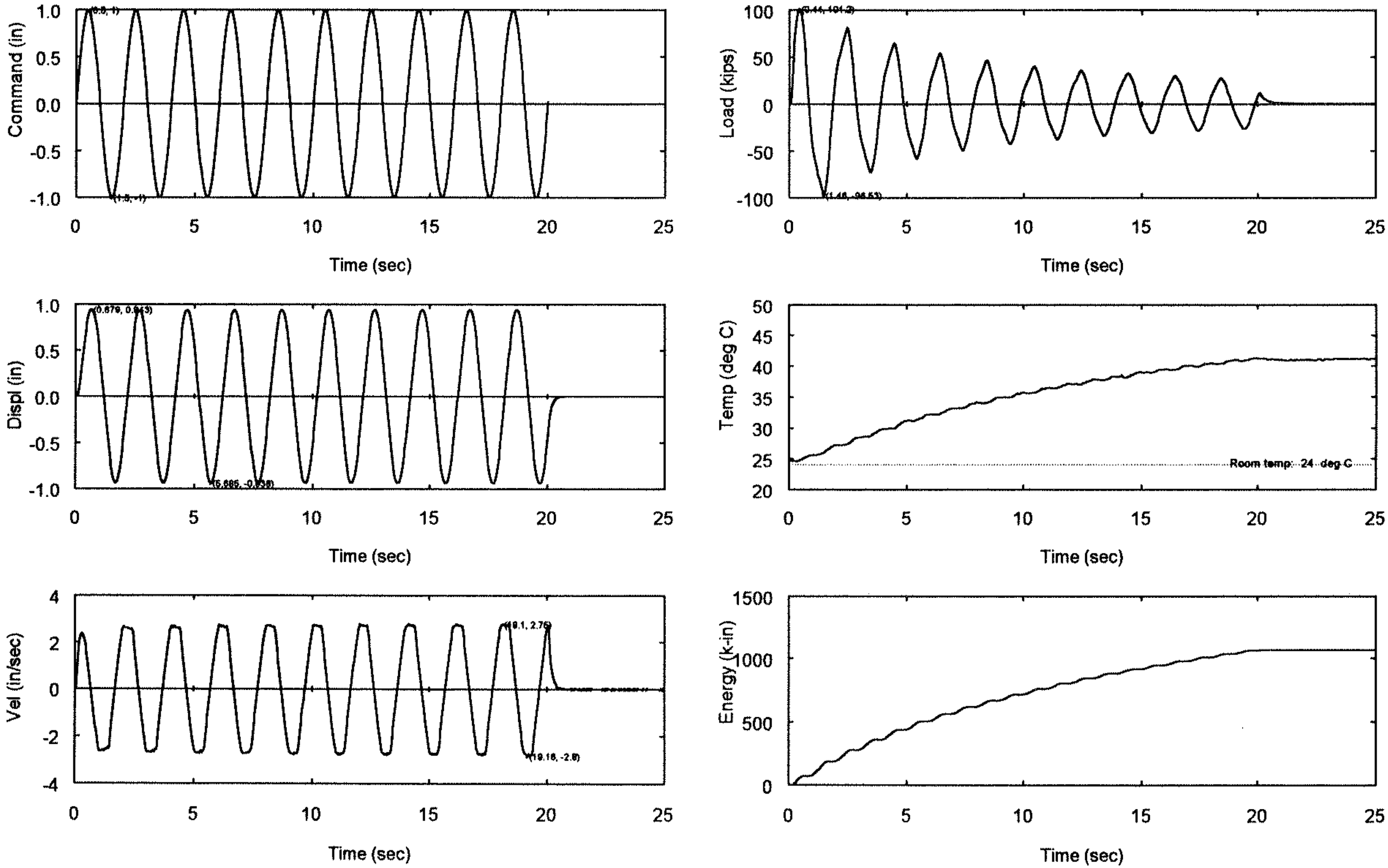
Test date: June 10, 1993 File: d2h308.txt





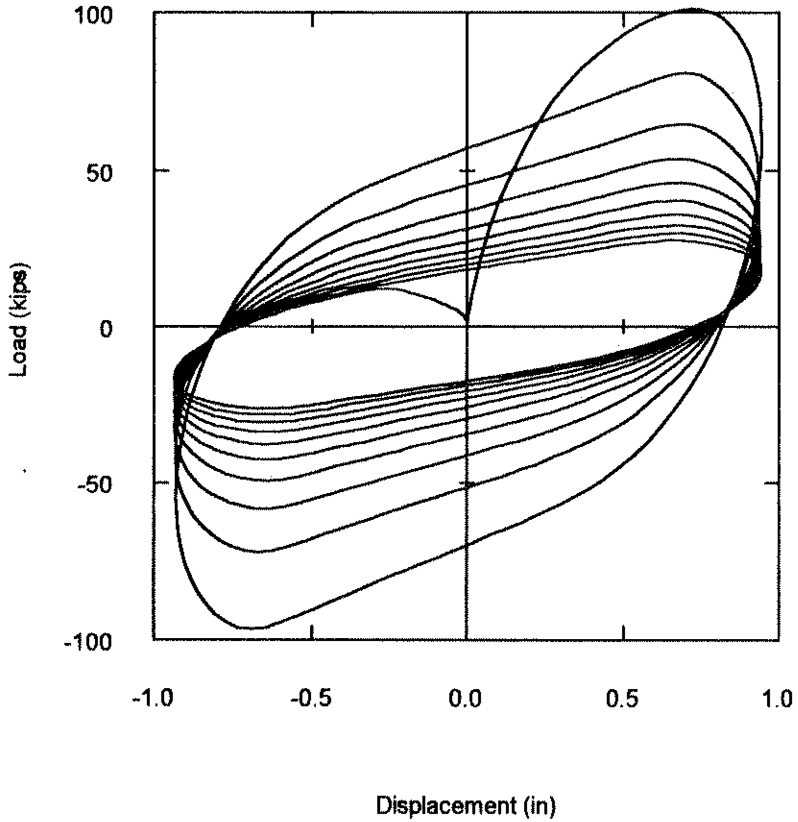
Damper No. 2 Harmonic 10 Cycle Test - Dmax = 1.0"

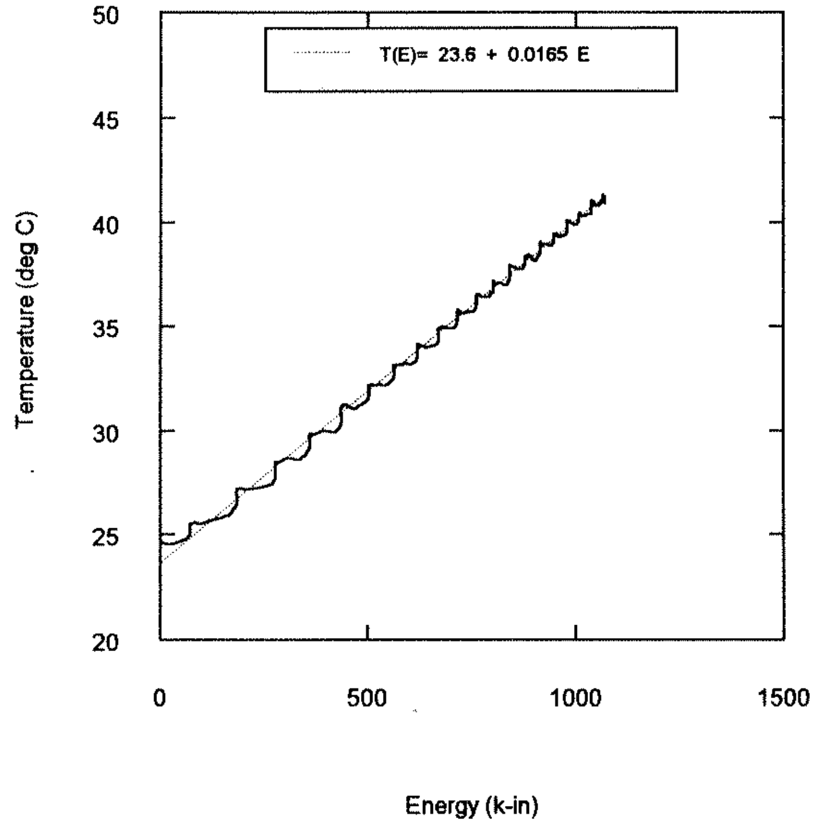
Test date: June 10, 1993 File: d2h1010.txt



Damper No. 2 Harmonic 10 Cycle Test - Dmax = 1.0"

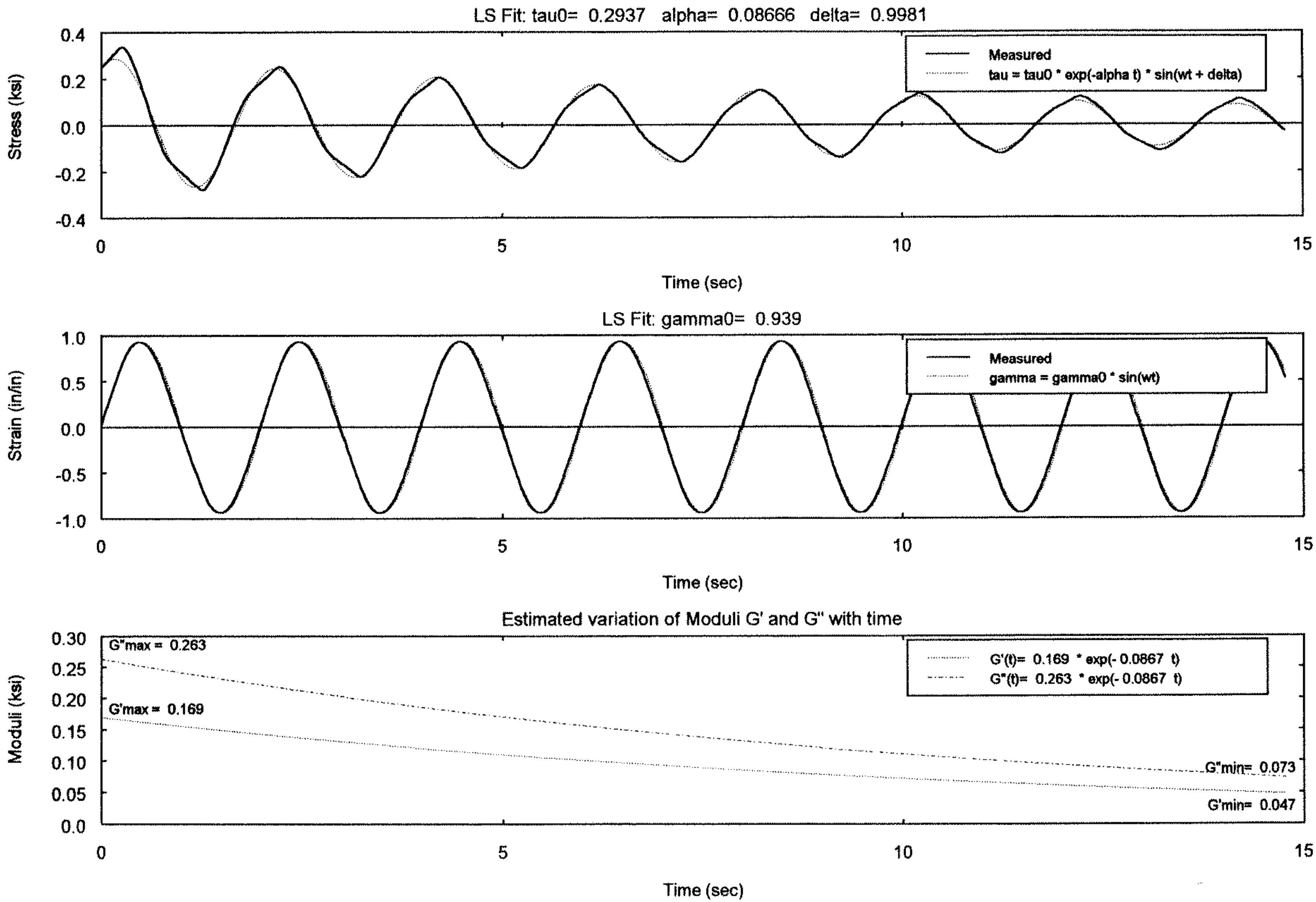
Test date: June 10, 1993 File: d2h1010.txt





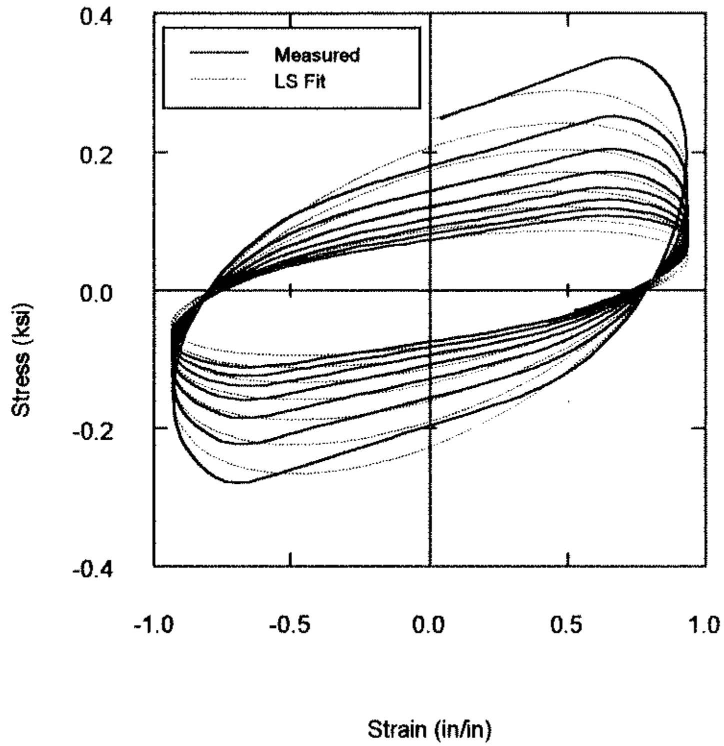
Damper No. 2 Harmonic 10 Cycle Test - Dmax = 1.0"

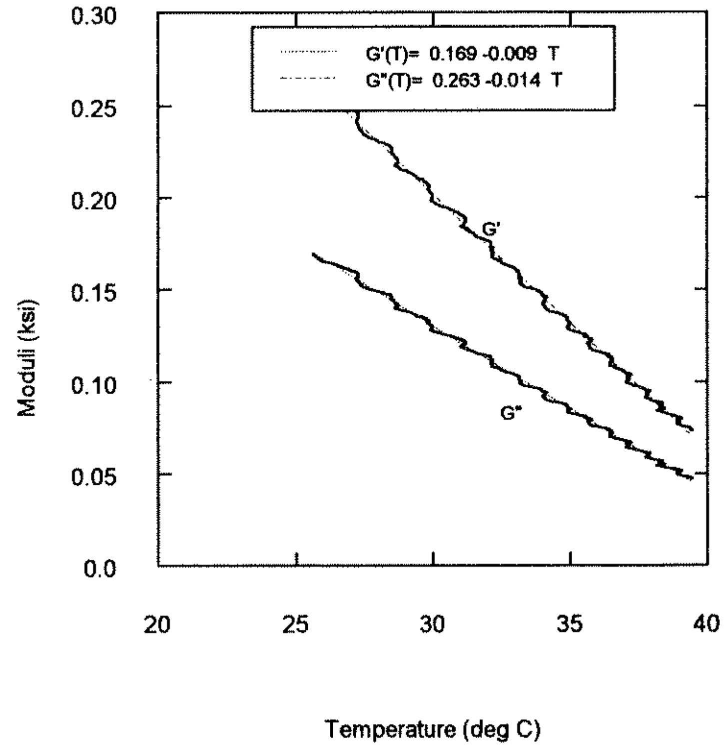
Test date: June 10, 1993 File: d2h1010.txt



Damper No. 2 Harmonic 10 Cycle Test - Dmax = 1.0"

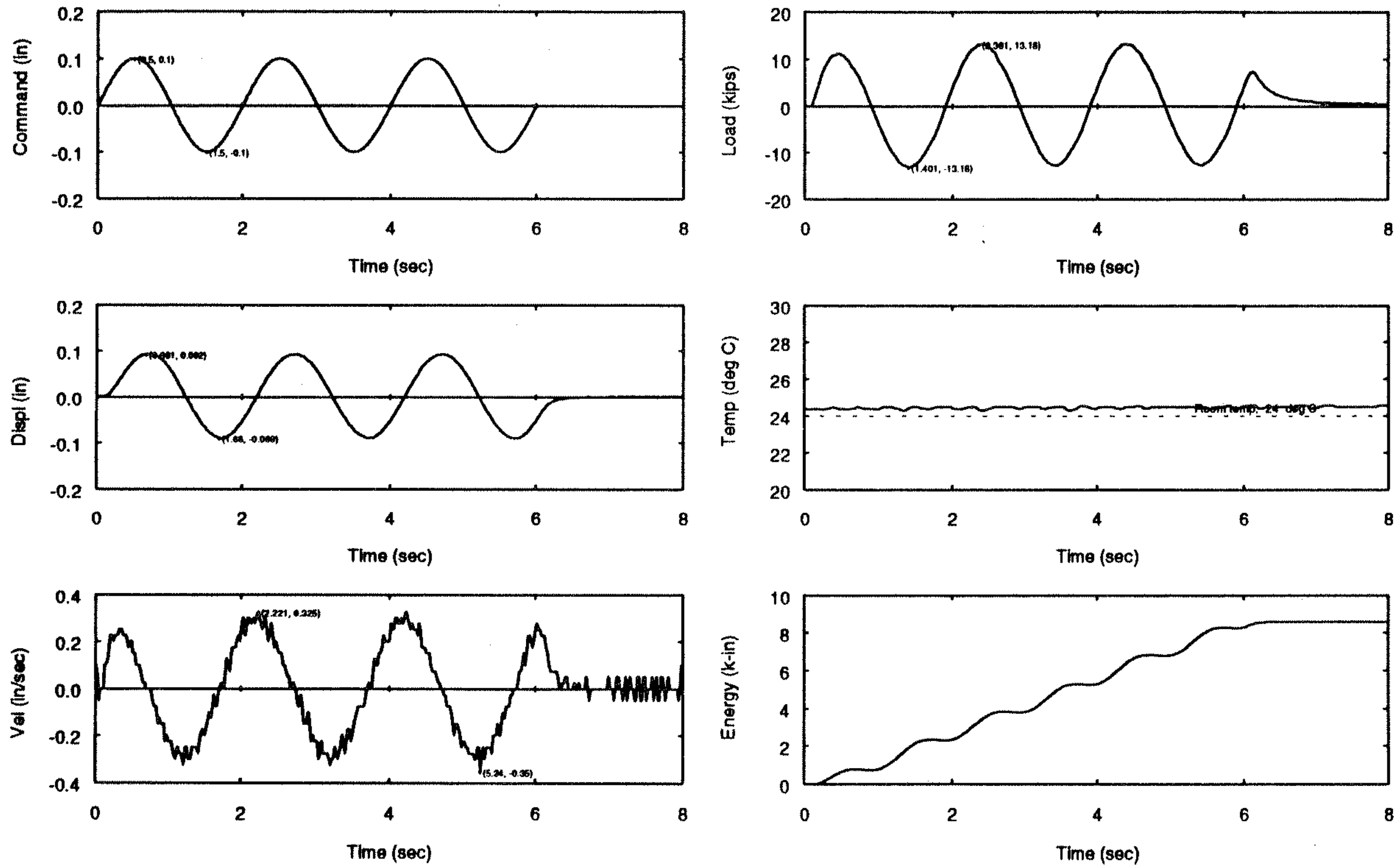
Test date: June 10, 1993 File: d2h1010.txt





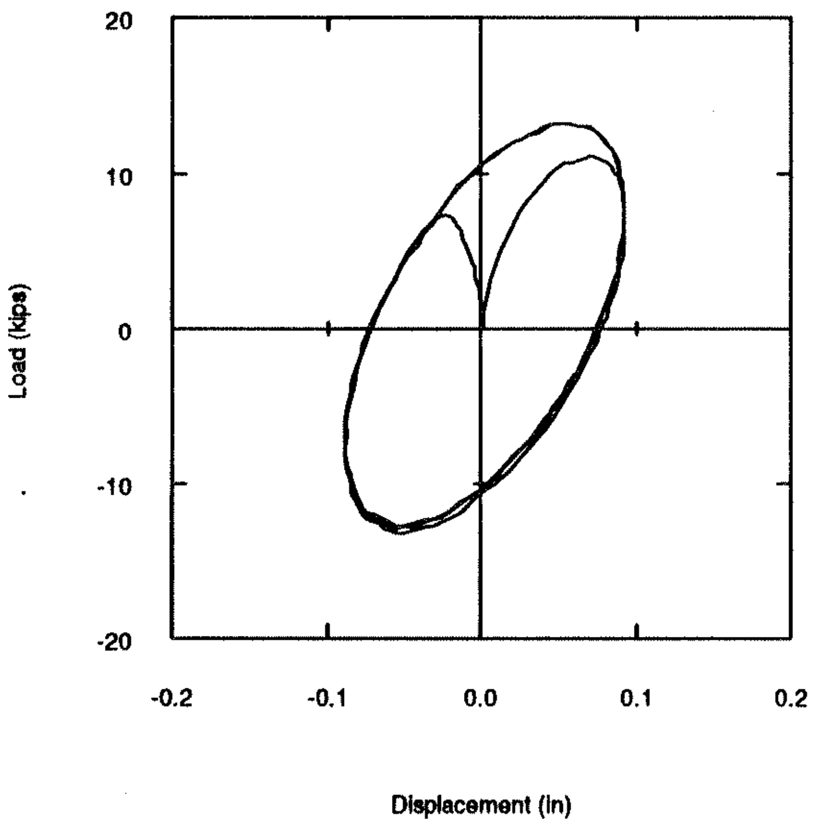
Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.1" (2nd test)

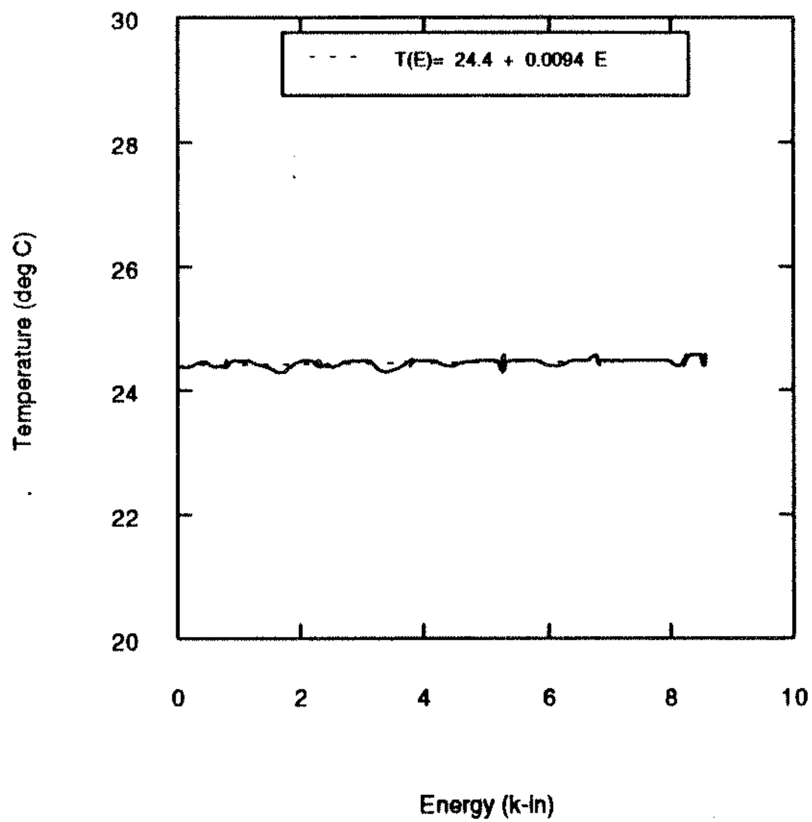
Test date: June 10, 1993 File: d2h301a.txt



Damper No. 2 Harmonic 3 Cycle Test - Dmax = 0.1" (2nd test)

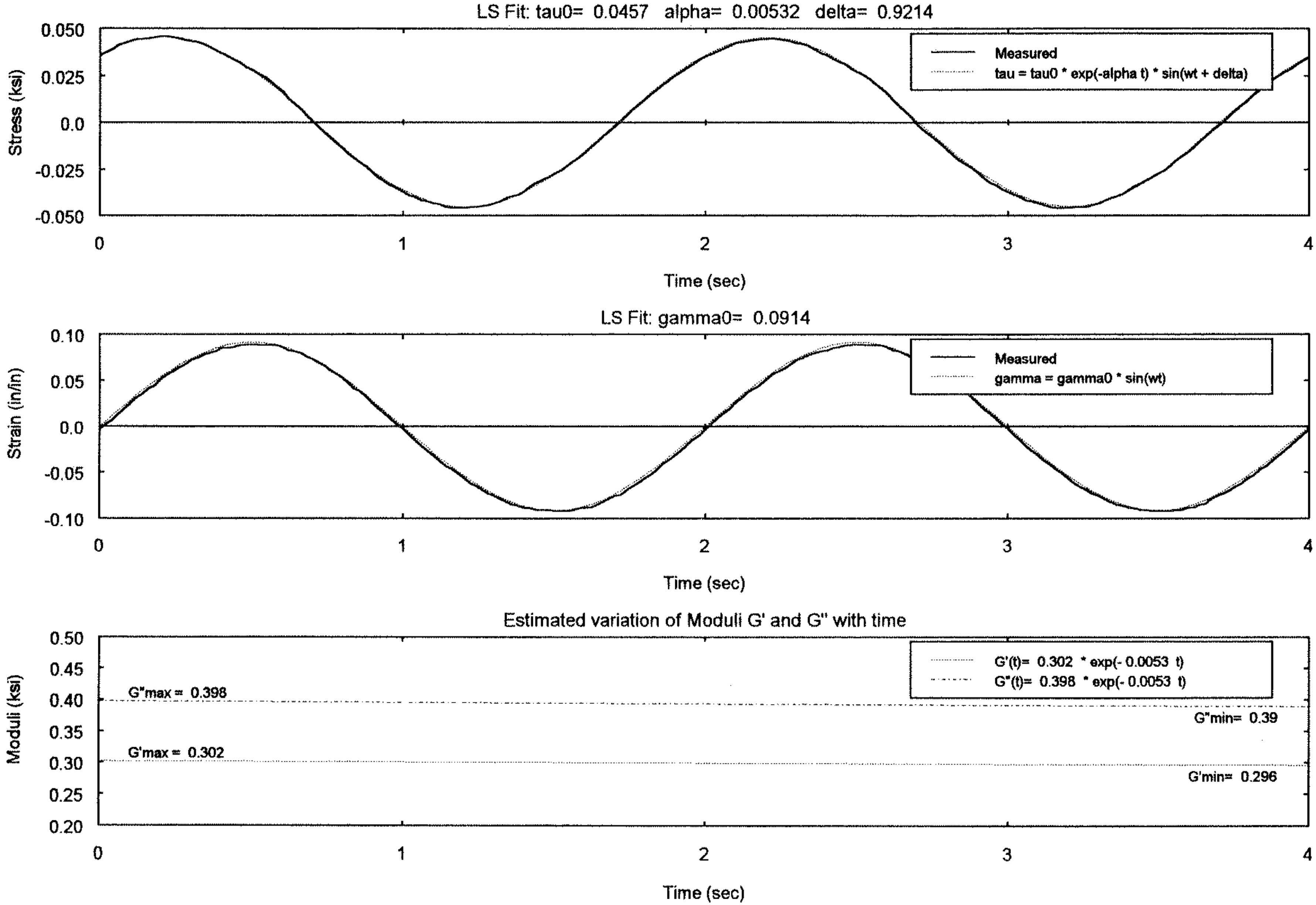
Test date: June 10, 1993 File: d2h301a.txt





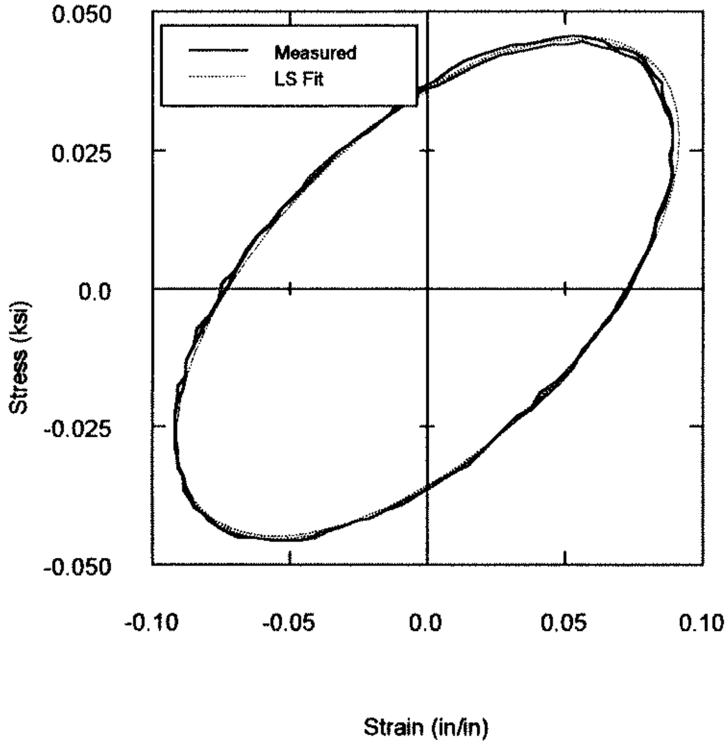
Damper No. 2 Harmonic 3 Cycle 2nd Test - Dmax = 0.1"

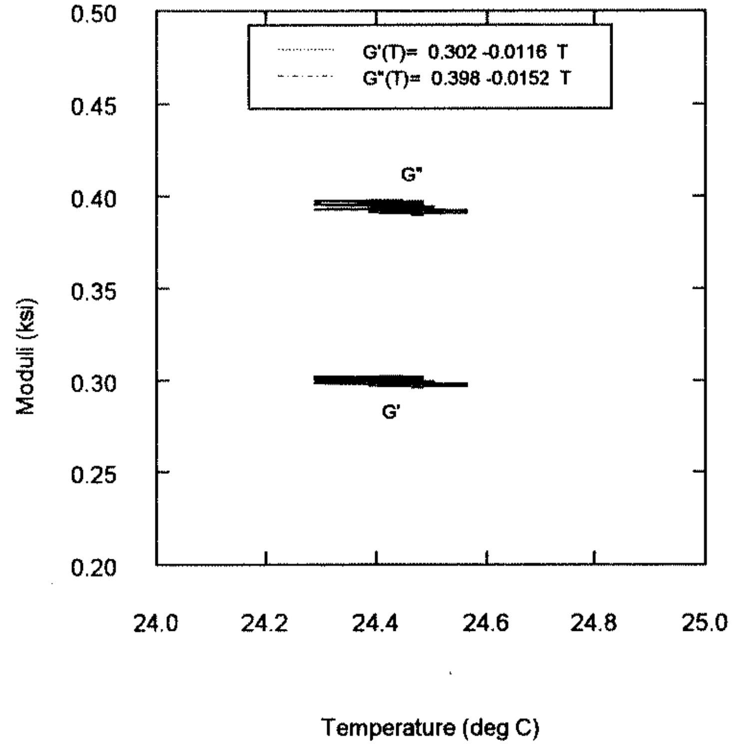
Test date: June 10, 1993 File: d2h301a.txt



Damper No. 2 Harmonic 3 Cycle 2nd Test - Dmax = 0.1"

Test date: June 10, 1993 File: d2h301a.txt





APPENDIX B

SHEAR FAILURE TESTS

University of California at Berkeley
Department of Civil Engineering

ULTIMATE SHEAR BEHAVIOR OF SMALL VISCOELASTIC DAMPERS

Report to

Professor James M. Kelly

By

Marcial Blondet

May 1993

1. Introduction

This report briefly describes the results obtained during a test program on the ultimate shear response of Polymer 109, a viscoelastic material used in structural dampers manufactured by 3M Corporation. The main objective of the test program was study the shear behavior of the material when subjected to transient dynamic loading. Another goal of the program was to determine whether shear failure was controlled by strain level or stress level.

2. Test setup & instrumentation

The test program consisted of subjecting six small "dampers" to pure shear and measuring their load and deformation response. Shear deformation was applied at a constant rate for each specimen, and varied from specimen to specimen.

The six dampers were fabricated by 3M Corporation. They were identified by the code 98469-28x, where x is A through F. They consisted of two blocks of viscoelastic material measuring 0.5" x 1.5" x 2.0" sandwiched between steel plates, as shown in Figure 1.

All specimens were tested on the 35 kip dynamic testing machine existing at the Structural Dynamics laboratory in 145A Davis Hall. The central steel plate was attached to the load cell at the top of the testing machine. The side plates were connected to the piston of the actuator located at the bottom of the testing space. A state of stress close to pure shear was induced in the viscoelastic material by loading the specimen in tension. (Notice, however, that since the bottom plates were kept at a constant distance, some tension in the horizontal direction must have occurred at large deformation levels.)

The applied load was measured with a 10-kip load cell. Specimen deformation was measured with the LVDT built into the system to measure the actuator's stroke. Two linear potentiometers were also installed to measure the deformation with greater precision. Analysis of the recorded data suggested that the stroke measurements were sufficiently accurate for the purposes of the tests. The additional displacement measurements are thus considered redundant and are not presented here. Room temperature was monitored with a thermocouple. Figure A includes two photographs of the specimen and equipment setup.

The data acquisition and control system hardware consisted of a Metrabyte DAS 1601 card installed in a 50-Mhz 486 PC. The Autonet program was used to collect the experimental data and control the actuator of the testing machine.

3. Test results

All tests were performed on May 11, 1993. Marcial Blondet was responsible for the planning and execution of this project in coordination with Professor James Kelly and Dr. Mig-Lai Lai. Marcial Blondet configured the Autonet data acquisition and control system and conducted the experiments. Todd Merport installed and tested all the electronic instrumentation and helped in the performance of the tests. Hany Khechfe videotaped the tests and photographed the equipment and specimens. Dr. Lai witnessed the tests.

All specimens were tested under displacement control. The command function supplied to the testing machine was a ramp function, i.e. actuator stroke was specified to increase at constant rate. The displacement rates were selected from very slow (0.1 inches/second) to the fastest velocity that the system could achieve. For this case, the command signal was a step function which specified to apply instantaneously a displacement of 6 inches.

A number of accidents occurred during the tests. Data for specimen B were not recorded due to operator error (MB). A "bug" in the Autonet software caused the destruction of the data file for specimen D. Finally, specimen E was destroyed due again to operator error (MB) and no data could be collected. Fortunately, the load versus deformation curves for specimens B and D could be recovered by digitizing printouts of the computer screen. The digitization error is estimated at 3%.

The mode of failure was similar for all specimens. Failure occurred at very large strain levels (larger that 300%), by tearing of the viscoelastic material along planes from the top of the side plates to the bottom of the central plate. Figure 3 includes photographs of some specimens after failure. Room temperature during the tests varied between 74 and 77 degrees Fahrenheit.

Table 1 summarizes the main results obtained.

Table 1. Summary of test results.

ID	Target Rate (in/sec)	Meas'd Rate (in/sec)	Strain Rate (in/in/s)	Max Load (kips)	Max Displ. (in)	Max Stress (ksi)	Max Strain (in/in)
A	0.10	0.10	0.20	3.08	2.21	0.513	4.42
C	0.50	0.50	1.00	4.66	1.99	0.777	3.98
D	1.00	1.04	2.08	5.13	1.85	0.855	3.70
E	1.50	1.46	2.92	5.70	1.76	0.950	3.52
B	∞	1.72	3.44	5.73	1.64	0.955	3.28

The displacement rate provided by the testing machine was very close to all the finite target rates. For the case of the maximum possible rate (specimen B) the system responded at a displacement rate of 1.72 in/sec. (The actuator's servovalve has a rated capacity of 25 gpm, which corresponds to a velocity of 1.5 in/sec.) The shear strain applied to the dampers varied between 0.2 in/in/sec and 3.44 in/in/sec.

Figure 4 shows the stress-strain curves obtained for the five specimens successfully tested. These curves show that the shear response of the material is extremely dependent on the strain rate. As expected, for increasing strain rates the ultimate shear stress increases and the ultimate strain decreases.

The shape of the stress-strain curves also varies with strain rate. For high strain rates (dampers D, E and B with rate > 1 in/sec) the curves start with a relatively high stiffness (tangent shear modulus G) which decreases with increasing strain level and stabilizes at about 0.18 ksi. For the specimens tested at lower strain rates (dampers A and C, with rate < 1 in/sec) show three stages: high stiffness for very low strains which first decrease and then increase with increasing strain levels, to finally stabilize at about 0.18 ksi before failure.

Figure 5 shows plots of the measured ultimate stress and strain versus the applied shear deformation rate. Notice that the range of shear deformation rate is from 0.1 in/sec to 1.72 in/sec. The fastest test was therefore 17 times faster than the slowest test. Ultimate strain changed from 4.42 in/in (slowest test) to 3.28 in/in (fastest test) or decreased by 26%. Ultimate stress, however, changed from 0.513 ksi (slowest test) to 0.955 ksi, or increased by 86%. In a sense, therefore, it can be concluded that the ultimate shear behavior of the viscoelastic material is more strain-dependent than stress dependent.

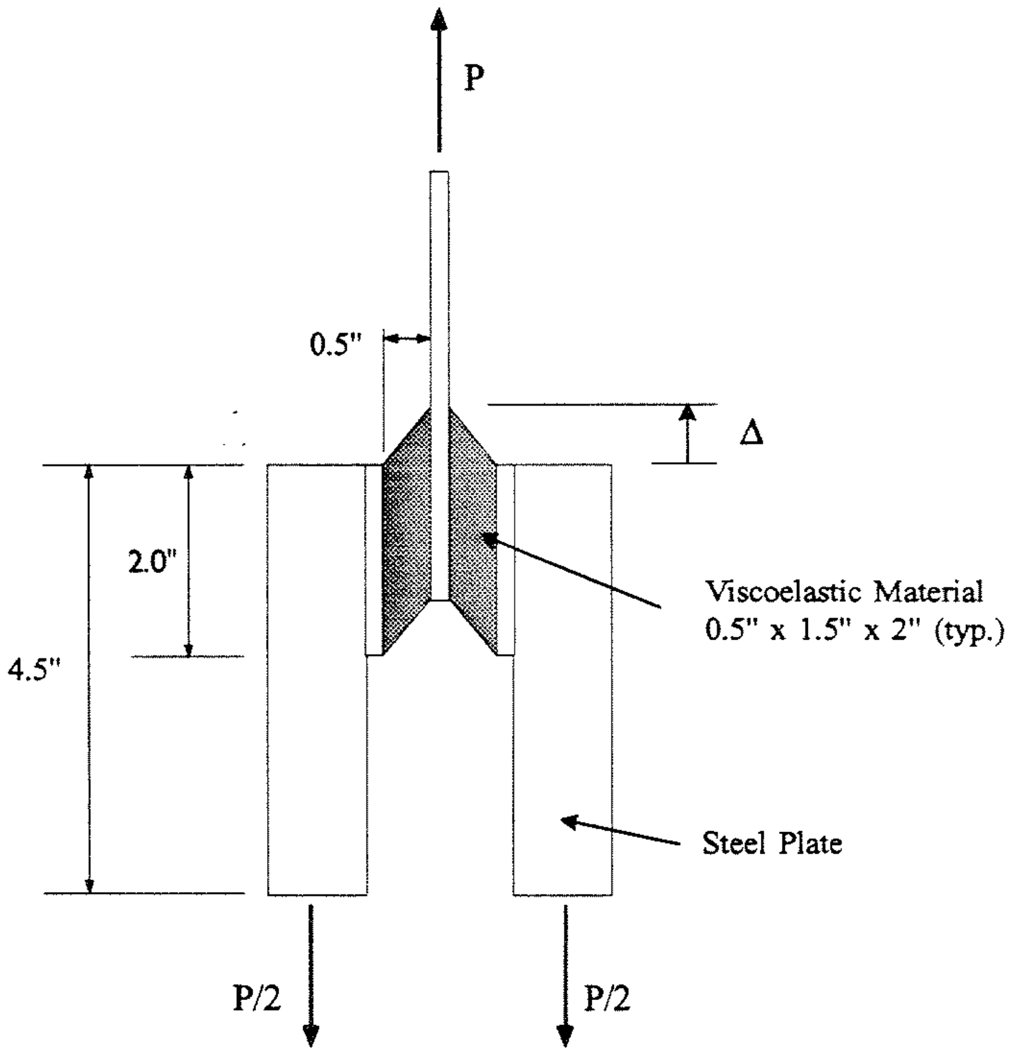


Figure 1. Test specimen dimensions.

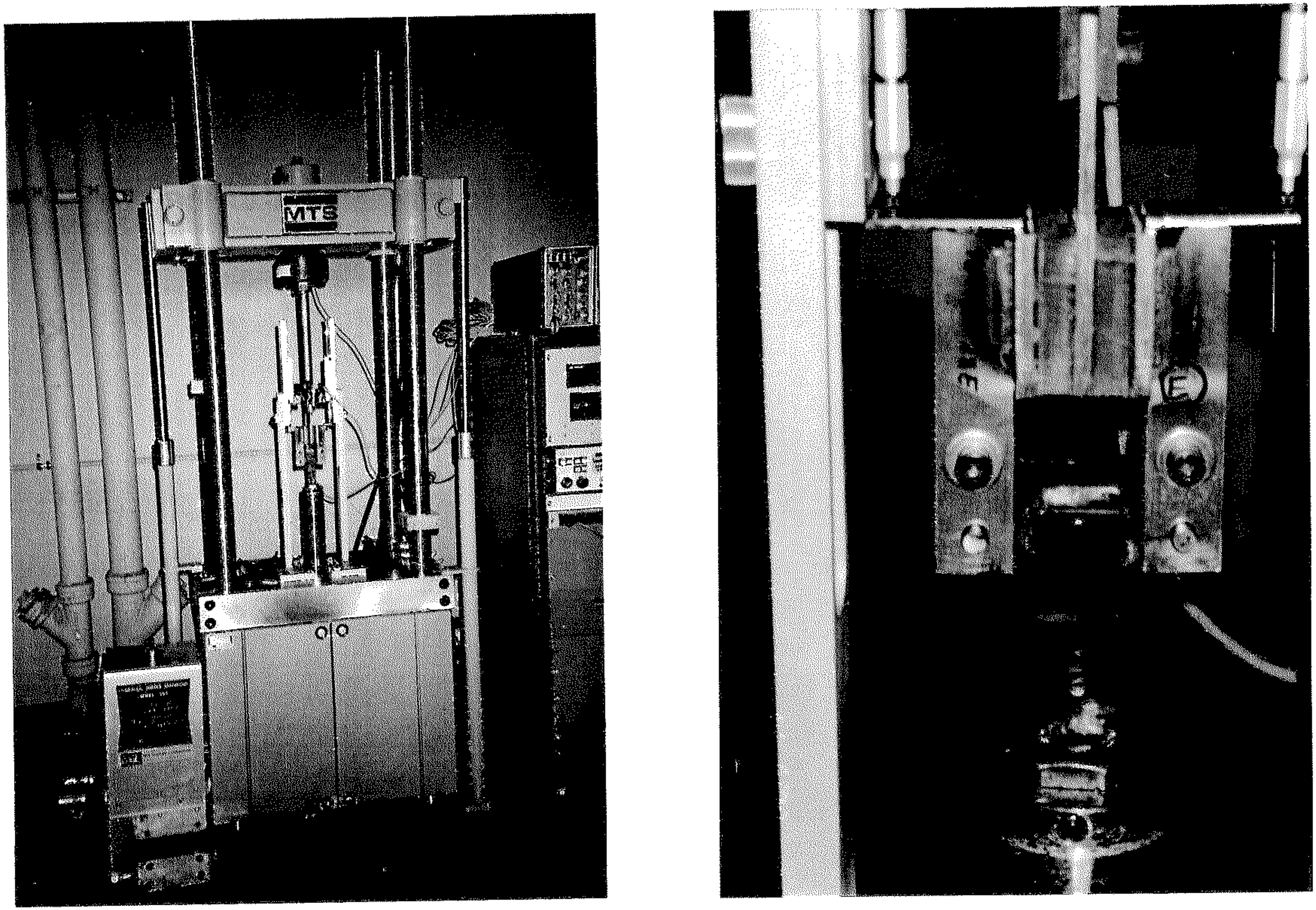


Figure 2. Specimen & equipment setup.

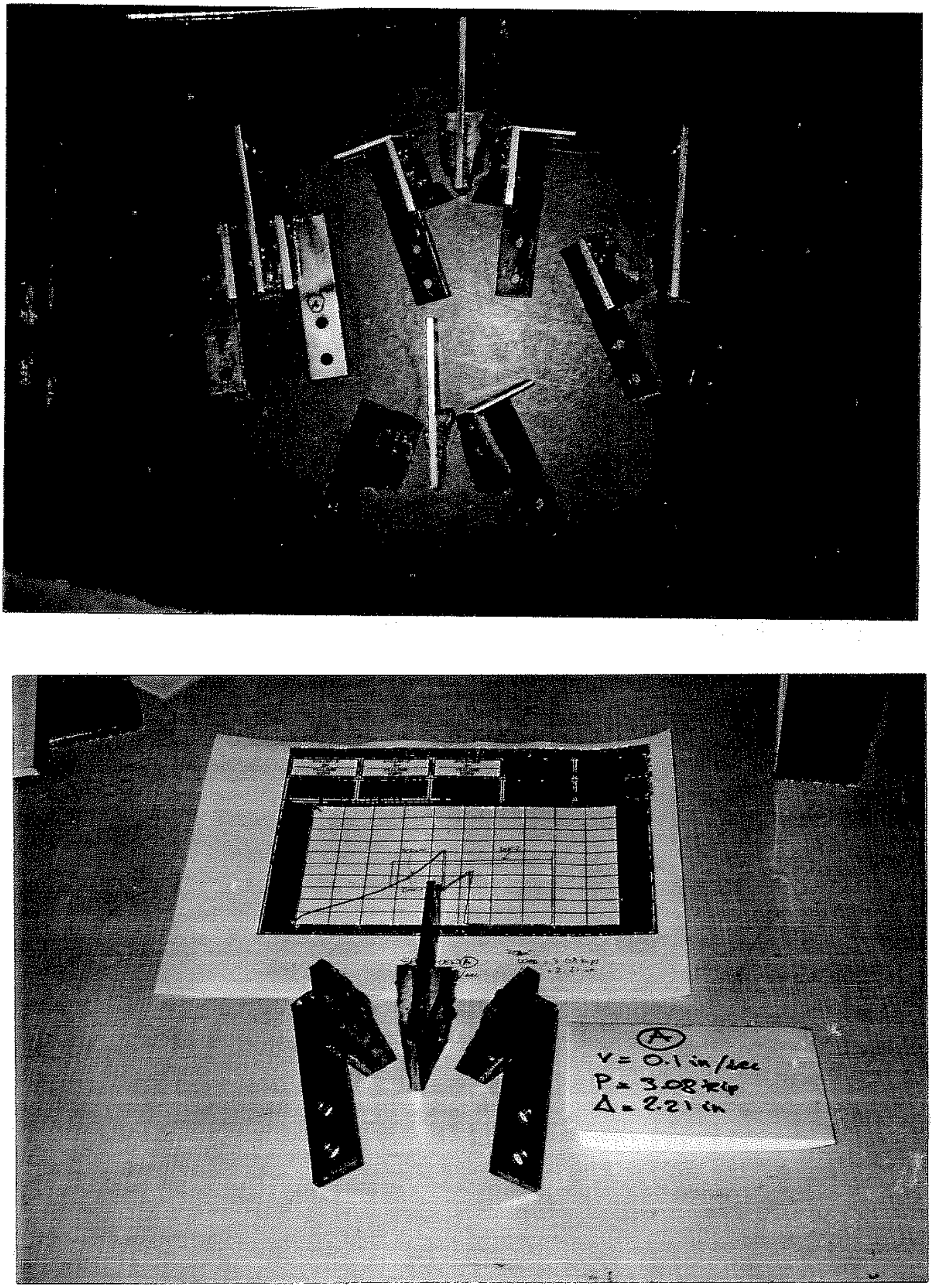


Figure 3. Specimens after shear failure.

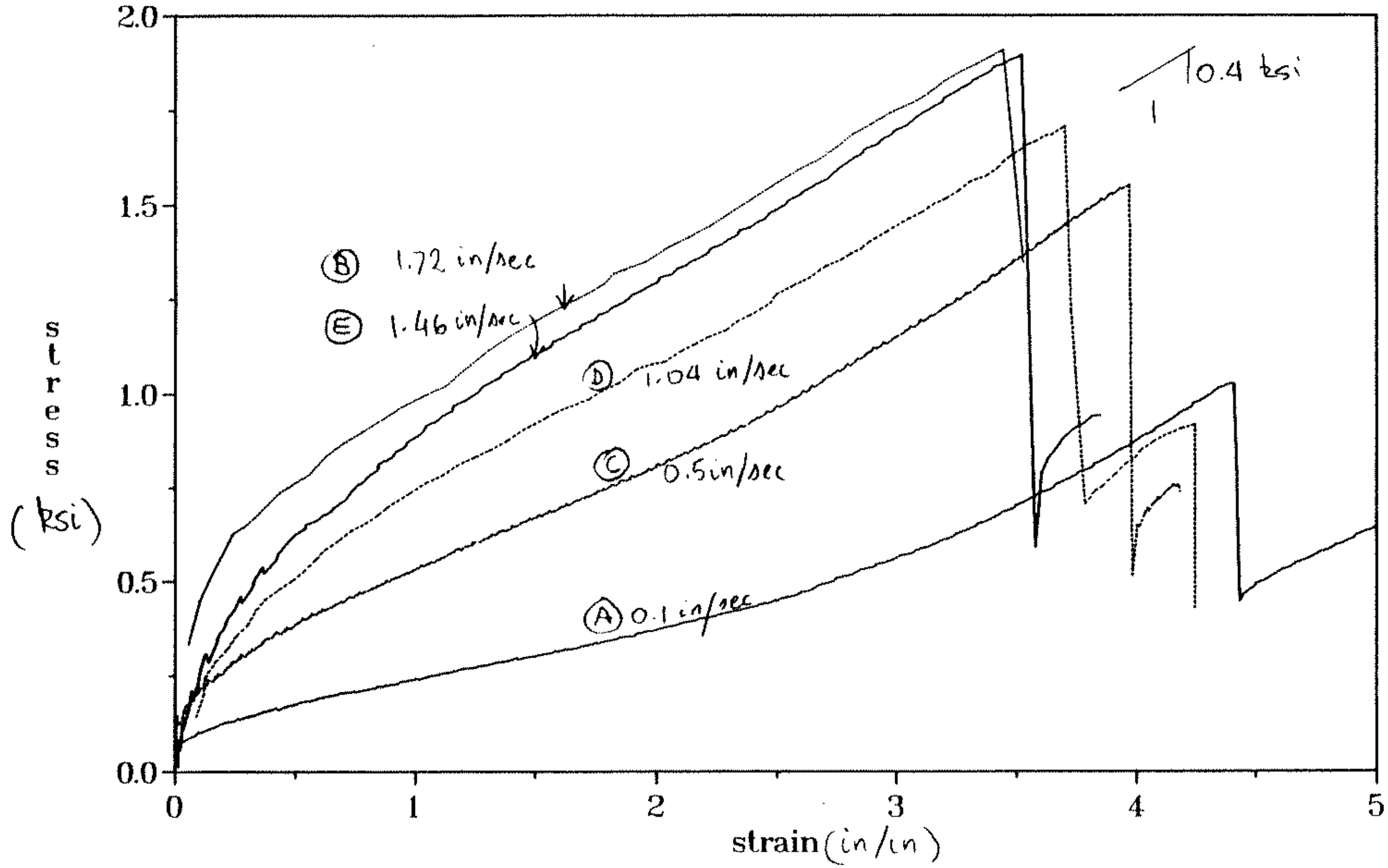


Figure 4. Stress versus strain curves.

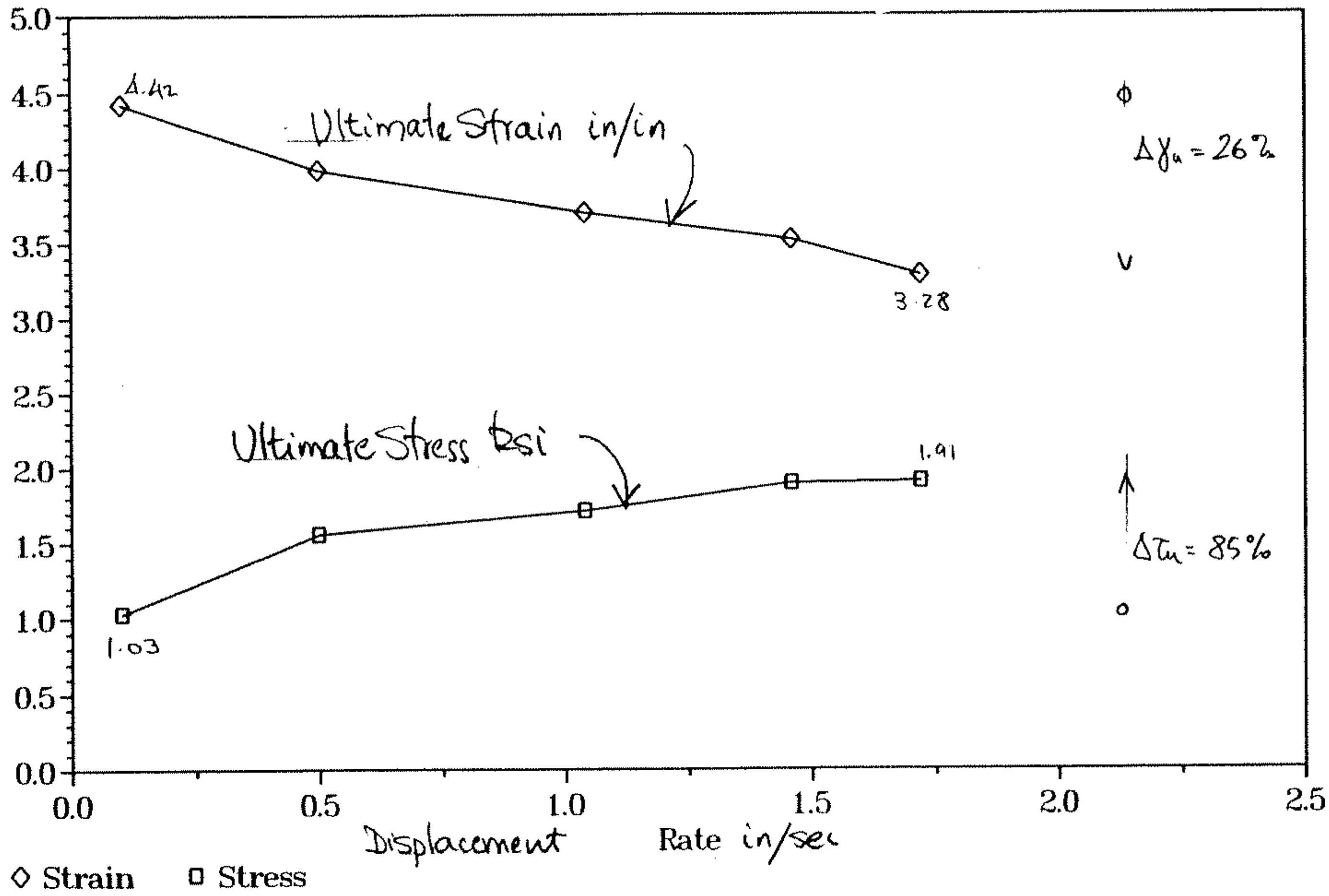


Figure 5. Ultimate stress and ultimate strain versus shear deformation rate.