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EXPERIMENTAL TESTING OF AN ENERGY-ABSORBING BASE ISOLATION SYSTEM

by
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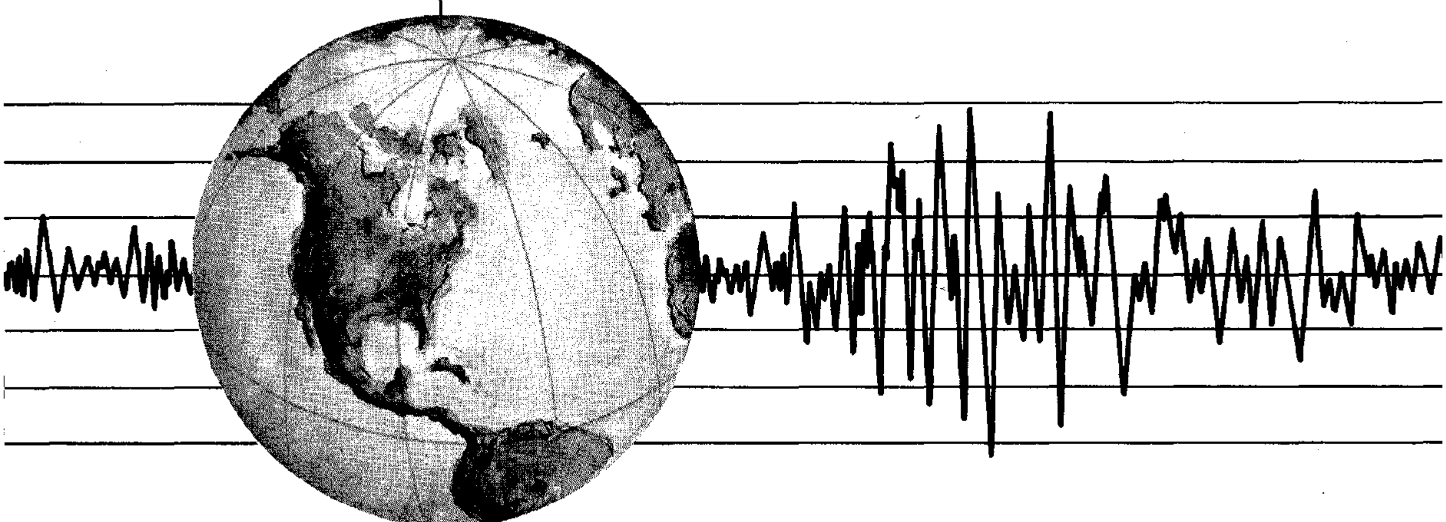

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After the energy-absorbing device had been subjected to a series of preliminary static tests designed to determine the hysteretic behavior of the device, the natural rubber bearings and devices were incorporated in an 80,000 lb structural model. The model was mounted on a twenty-foot square shaking table and subjected to a range of earthquake ground motion. Relative displacements at the natural rubber bearings were considerably lower with the devices installed, while structural accelerations were not increased significantly. Reduction of the displacements at the bearings of an isolation system such as that described here is necessary to ensure that the bearings remain stable under load. When both the energy-absorbing device and natural rubber bearings were in place, the structural model withstood simulated earthquake ground motions of extremely high intensity.

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ABSTRACT

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I. INTRODUCTION

The research work to be described here concerns an experimental study of the use of a new type of energy-absorbing device incorporated in an aseismic base isolation system. The purpose of the device is to absorb the kinetic energy induced in a building or structure carried by the base isolation system but the device also acts to restrain structural movement under wind loads and to increase the natural period of an isolated building on yielding of the device. This lengthening of the natural period of the building during a severe earthquake usually will reduce the accelerations felt by the structure. It is generally accepted that a structure designed to resist earthquake attack must have some capacity to dissipate energy; this capacity is normally provided by detailing beam-column connections so that they can accept a certain amount of plastic deformation. The inherent ductility of a structural system so designed assures that it will survive, even if damaged, the largest foreseeable earthquake. However, the provision of ductility in a structure the primary purpose of which is to carry vertical load means that if this energy-absorbing capacity is used, some damage to the structure will result. Thus, the question arises as to whether it is possible to incorporate into a structure a set of replaceable devices specifically designed to absorb energy and the consequent damage that would under conventional design methods be absorbed at beam-column connections.

Several applications of energy-absorbing device have been proposed and a number of structures incorporating such devices are now being or have been constructed. A review of the state-of-the-art of energy-absorbing device applications to aseismic structural design is given in reference 1.

One obvious application of energy-absorbing devices is in conjunction with an aseismic base isolation system. Large displacements are necessary to dissipate large amounts of energy at reasonable force levels. A characteristic of base isolation systems is that while they reduce acceleration levels, the reduction is at the cost of large relative displacements between the superstructure and the foundation. These large displacements can, however, be turned to advantage by including energy-absorbing devices which act to control displacement and by yielding simultaneously limit the base shear experienced by the building.

For most buildings and structures in California the peak design accelerations are no higher than 0.4g and a simple rubber bearing base isolation system will suffice. For nuclear plants, however, the very low probability of seismic events for which the plant must be designed requires a design peak acceleration which may be as high as 1.0g, much higher than can be accommodated by a simple base isolation system. The energy-dissipating base isolation system in which rubber bearings and solid state devices are integrated then becomes essential. No other structural design strategy can simultaneously protect a structure at these peak acceleration levels and also protect sensitive internal equipment.

A series of experiments on a large structural model, a natural rubber base isolation system, and a new design of energy-absorbing device has recently been completed on the 20 ft x 20 ft shaking table at the Earthquake Simulator Laboratory of the Earthquake Engineering Research Center, University of California, Berkeley. The energy-absorbing device used in these tests is similar to a device described by Tyler [2]; this device has been used in a highway bridge in New Zealand where it operates in horizontal motion in the buttresses of the bridge.

II. ASEISMIC BASE ISOLATION

Base isolation is an antiseismic design strategy founded on the prèmise that a building can be decoupled from the damaging horizontal components of earthquake ground motion through a mechanism that prevents or at least attenuates the transmission of horizontal acceleration into the building. Many unimplemented base isolation systems have been proposed, see reference 3 for a review, ranging from ball bearings to inverted suspension systems, but the concept has become a practical reality in recent years with the development of multilayer elastomeric bearings. These bearings have been developed for highway bridges [4] to allow for thermal expansion, for helicopter rotors [5] and for wharf fenders [6]. They have recently been used to isolate buildings from the effects of ground-borne acoustic vibration [7]. Some very large buildings have been constructed on multilayer bearings, e.g. the Berlin Conference Hall [8].

Bearings for use in an aseismic isolation system are a natural development of acoustic isolation bearings and although they differ in design, the manufacture, materials and installation would be similar. In fact, there are two systems based on natural rubber which have been or are being implemented, namely three small school buildings in France on a system designed by Delfosse [9] and a government building on a combination natural rubber/lead system now under construction in New Zealand [10]. A nuclear power plant (Kroeberg) on a neoprene bearing topped by a slip plate system is presently under construction in South Africa [11].

There has been some resistance in the engineering profession to the use of base isolation as an aseismic design strategy connected with a lack of confidence and experience in the use of elastomeric materials in engineering applications, but experience with bridge bearings over many years has demonstrated that they are reliable, long lived, and resistant to environmental damage, including damage from oil and fire [12].

The most compelling argument for the use of base isolation is the protection that it affords internal equipment and piping. The main structure of a building or power plant can be protected from earthquake attack with relative ease, but strengthening the main structure increases the seismic loads transmitted to nonstructural components and equipment. In many structures such components can be an order of magnitude more costly than the building housing them, an important consideration in the design of essential equipment such as pumps, valves, and control devices, and piping systems in nuclear and, recently, geothermal power plants in seismically active regions. The response of nonstructural components is determined by the response of the primary structure to the earthquake; the design process for such components is particularly difficult, complicated both by uncertainties in the specification of the ground motion and by uncertainties about the properties of the primary structure.

The standard design approach is the floor spectrum method which requires many time-history analyses to be performed on the primary structure using a set of earthquake ground motions consistent with the design spectrum for the plant to determine the response at the attachment points of the equipment items. Each analysis is deterministic and many must be performed to reflect the probabilistic nature of the problem. A further complication arises in the case of piping systems: here, the secondary structure (the piping system) may be attached at many different support points each of which experience different displacement time histories for the same ground motion. There then arises the problem of combining by the floor spectrum method the contributions to a particular response quantity from each support motion. There are several proprietary piping analysis programs which perform such analyses, but their use is controversial at least and extremely costly. A further complication arises when the natural frequency of the equipment or piping system is close or equal to one of the natural frequencies of the primary system, a situation referred to as tuning and one almost inevitable in a large system. The interaction between the equipment and the structure in such a case can be highly significant even in relatively light equipment [13,14]. The floor spectrum method neglects this interaction and is invalid for such cases; if used, equipment response can be significantly overestimated, leading to excessively conservative equipment design [15].

Peak earthquake levels for which nuclear and geothermal power plants must be designed have been steadily increased by regulatory agencies over the past several years. One response to such increases has been the proposal that inelastic action be permitted in the equipment and its supports and another that energy-absorbing restrainers be used in piping systems. Since plastic deformation produces a drop in the frequencies of a system and an energy absorption, the response of the equipment and piping would theoretically be lowered to a level below that which would prevail if the system were to remain elastic. However, plastic action inevitably involves some damage to equipment supports or to the primary structure and also requires nonlinear deterministic analyses of both the primary and secondary systems.

An alternative approach is to construct the entire power plant on a base isolation system, involving a double layer foundation with the lower element fixed to the ground and the upper element separated from the lower by a decoupling mechanism. The major benefits of base isolation to equipment and piping design are that consideration of equipment-structure interaction and inelastic response becomes unnecessary and, due to the fact that the primary structure above the isolation system moves as a rigid body, the displacement time histories of all support points of a piping system are identical. Thus, multiple support response spectrum analysis, with its controversial aspects, need not be used. A further advantage is that the inelastic action will be concentrated at the lower level in devices which are replaceable after a major seismic event.

Considerable experimental testing of the concept of base isolation has been carried out on the shaking table at the Earthquake Simulator Laboratory. A number of base isolation systems have been tested to determine the influence of base isolation on the response of light internal equipment. The results of this work are described in references 16, 17, 18, and 19.

III. ENERGY-ABSORBING DEVICES

The energy-absorbing devices used in this test series are tapered, cantilever beams of hot-rolled, low carbon mild steel. The energy-absorbing mechanism is large elastic-plastic deformation. Based on experience with the torsional energy-absorbing devices described in references 17, 20, and 21, the devices were designed so that welding was not necessary for installation in the system. The tapered form of the cantilever with the point of application of force at the apex ensures that strain over the working portion of the device will be constant. In previous testing it was shown that this is a necessary condition to ensure continuing plastic action of the device.

At the maximum displacement to which the devices were subjected in the present test series, plastic strain was estimated to be 1.8%, equivalent to a ductility factor of 15 for the low carbon steel from which the devices were fabricated. Since the devices are elastic for small displacements, they act as mechanical fuses. The behavior of a structure on the bearing/device system is thus similar to that of a structure on a conventional foundation for minor excitations. While a structure so based will typically amplify ground acceleration under minor excitation, the device will yield under more intense excitation and produce large hysteresis loops as the structure oscillates. The tangent stiffness of the steel when yielded is between 5% and 10% of elastic stiffness. Thus, the fundamental frequency of the structure is lowered and the system acts as a highly damped isolator. The accelerations induced in the structure are of course slightly greater than if only a rubber bearing isolation system were used, but the displacement at the bearings is reduced. The degree of damping introduced by the energy-absorbing devices strongly depends on ground motion intensity.

IV. STATIC TESTING OF CANTILEVER DEVICES

Six cantilever devices were machined from 1020 mild steel to the dimensions shown in Figure 1. These specimens were subjected to displacement-controlled, pseudo-static loading to verify that the device could produce the energy absorption needed for the isolation system and that the device would survive several cycles of tests.

The devices were tested on an MTS Hydraulic Service Manifold Series 284 testing machine coupled with an MTS Servogram Model 204-31, 50-kip capacity hydraulic ram and loading rig; input to the system was displacement controlled. All devices were subjected to cyclic sinusoidal loading; in addition two of the devices were subjected to a random loading with a known return period to verify that behavior of the device under sinusoidal loading could be correlated to that under seismic loading. Ram displacement was measured by the control console (MTS Model 483.02). The applied load was measured by a load cell incorporated in the ram arm and these measurements were used to generate hysteresis loops for each device tested. In addition, simultaneous plots were made of the applied load as a function of time for the sinusoidal loading cases. A variable voltage function generator with a range of $\pm 10V$ at 0.1 Hz provided the sinusoidal signal to the control console. The displacement maxima were altered by a variable amplifier integral in the console. Random loading with a repeat interval of approximately 100 seconds was similarly provided by a random noise generator. The random signal was first passed through a 20-Hz filter. Output from the generator was calibrated and offset to a maximum of approximately $\pm 10V$. The filtered signal is plotted in Figure 2. A simple schematic diagram of the experimental arrangement is given in Figure 3 and a photograph in Figure 4. Figure 5 is a photograph of a cantilever device in the test rig.

The cantilever devices (Figure 1) were loaded by means of a 1-in. pin located 1-7/8 in. from the axis of the cantilever. Six of these devices were tested during the experimental program. Due to the eccentric location of the pin, the response of the cantilever device was slightly asymmetrical. The cantilevers were press fit to the base into slots cut in a 1-in. thick base plate, itself fixed to the testing base, and welded beneath to simulate a built-in end condition.

Three cantilever devices were tested under sinusoidal loading of 0.1 Hz at displacements of ± 1 in. and ± 1-1/2 in. The displacement required to induce initial yielding of the specimens was approximately 1/4 in. The devices were loaded to roughly six times their original maximum elastic displacements.

The first cantilever device, number 101, was tested continuously at a displacement of ± 1 in. The specimen first yielded at 2.9 kips. Peak loads exceeding this value were recorded during this test with values of 4.0 kips and -3.3 kips. The difference in these peak values can be attributed to the asymmetry of the test set-up. Force-displacement hysteresis loops and force versus time curves were continuously recorded. Testing was terminated at 300 cycles; the hysteresis loops for device response indicated that only slight deterioration had occurred.

A second cantilever device, number 102, was similarly tested at ± 1 in. sinusoidal loading at 0.1 Hz for 200 cycles. Again, the device first yielded at 2.9 kips with maxima of 4.0 kips and -3.3 kips. After 200 cycles these values dropped to 3.8 kips and -3.2 kips, indicating that minor deterioration of the device had occurred. The displacement amplitude was then increased to ± 1-1/2 in. for an additional 60 cycles. Plots of hysteresis loops at the two amplitudes (Figures 6 and 7) indicate that no significant degradation occurred during the latter testing phase.

The third cantilever specimen, number 103, was tested at ± 1-1/2 in. for 150 cycles; no significant deterioration occurred. At 155 cycles, however, performance began to decay noticeably and the device abruptly failed at the 163rd cycle. The device fractured at the base of the neck of the cantilever, the thinnest section of the yielding portion of the element. Bending stresses will, there, be accompanied by higher shears than in any other section. Hysteresis loops of device response for cycles 11 through 163 are given in Figures 8 and 9.

Cantilever specimens number 104 and 105 were tested under random loading to simulate seismic loading. A period of close to 100 seconds was used so as to avoid similarity to a cyclic input. In the first such test of specimen 104 the input was scaled to a maximum displacement of 0.9 in. Force-displacement was recorded for 100-second intervals every 5 minutes. Peak forces for these individual plots were approximately 3.3 kips and -2.7 kips over the testing period with little deterioration. Hysteretic deterioration can be roughly estimated from these plots. The device performance was stable; no sign of failure appeared before testing was halted at 50 minutes.

Device 105 was also subjected to random input. The signal was scaled to 1.5 times that used in the test of device 104 with a resulting maximum displacement of 1.35 in. Force-displacement and time plots were again taken for 100-second intervals every 5 minutes (Figures 10 and 11). Maximum peak forces were 3.9 kips and -3.2 kips during the first 100 seconds; peak forces of 3.6 kips and -2.9 kips were observed until failure of the device at approximately 25 minutes. The device fractured completely at the base, with the fracture line curving slightly at each edge due to the flare of the cantilever design introduced to offset the effect of added bearing stresses induced by contact between the specimen and the base plate through which it was slotted.

The conclusions to be drawn from this test series are that the device was capable of sustaining prolonged dynamic loading with little deterioration in hysteretic response and that the behavior of the device under sinusoidal and random loading was sufficiently similar to allow results from sinusoidal testing to be extrapolated to seismic applications.

V. DYNAMIC TESTING OF DEVICES IN THE ISOLATION SYSTEM

The experiments reported here were carried out at the Earthquake Simulator Laboratory of the Earthquake Engineering Research Center, University of California, Berkeley. The model frame was tested on a 20 ft x 20 ft shaking table with associated control equipment as described by Rea and Penzien in reference 22. The shaking table is a prestressed concrete slab driven independently in the vertical and in one horizontal direction by servo-controlled actuators. Th

100-kip dead weight of the table plus the weight of the model is supported by differential air pressure during the operation of the table. The control signals for the two degrees of freedom are analogue displacement time histories on magnetic tape, normally obtained through a double integration of acceleration time histories of earthquake motion.

The limits of table motion when no model is present are given in reference 22. Displacement is limited by actuator stroke, velocity by oil-pumping capacity, and acceleration by actuator force capacity and the oil column resonance of the drive system. With a model on the table, the acceleration is further limited, but the other limits are not appreciably affected.

A NOVA 1200 minicomputer equipped with a Diablo 31 magnetic disk unit samples up to 128 data channels at rates of up to 100 samples/second/channel. Transducer signals pass through a NEFF system 620 Analog-Digital processor. The digitized data are then temporarily stored on the magnetic disk before being transferred to tape by a Wang 9 track magnetic tape drive for permanent storage.

The experimental model, shown in Figure 12, is a five-story frame mounted on two heavy (16WF) base floor girders supported by four rubber bearings. The load cells on which the rubber bearings rest are anchored onto the shaking table by high-tension stress rods. The dead load is provided by concrete blocks tied to the frame at the floor levels as shown in Figure 12. The blocks weighed 72 kips and the model frame 8 kips. A compressive force of approximately 20 kips was thus developed in each of the bearings. The dead load of the concrete blocks produced stresses comparable to those in a full-scale structure. The geometric scale factor of the model is roughly 1/3 with a corresponding time scale factor of $\sqrt{3}$.

The bearings, manufactured by the Andre Rubber Company Ltd., are of natural rubber reinforced by steel plates. A complete bearing comprises ten modules of two 1/4-in. thick layers of rubber and three 1/8-in. thick steel plates. The modules were epoxied together into units, but the epoxy did not transmit shear forces between layers of the bearing. Instead, steel disks 1/4 in. thick were keyed into circular holes in the 1/8 in. thick steel plates on the top of one module and on the bottom of the module directly above; these steel disks transmitted the shear forces. The bearings were keyed to the load cells at the bottom and to the steel frame at the top by similar disks. A typical bearing as installed is shown in Figure 13. At a vertical load of 20 kips, the horizontal stiffness of a single bearing was estimated to be 720 lbs/inch, corresponding to a horizontal natural frequency of 0.6 Hz for the 80,000 lb structure without energy-absorbing devices.

The instrumentation for the shaking table records average vertical and horizontal table displacement and acceleration and pitch, roll, and twist accelerations. The frame was instrumented to measure acceleration, displacement, and force. Horizontal accelerations in the frame were recorded by accelerometers on the base and on each floor level and vertical accelerations in the middle of the top floor level. The accelerometers were mounted on the concrete blocks to limit high-frequency noise.

Displacements were recorded by linear potentiometers with respect to a reference frame located to the left of the model and close to the table. The horizontal displacements were measured on the base level on either of the two base floor girders and on each floor level. Vertical displacements of the four bearings were measured and shear loads recorded by four load cells placed under the bearings (Figure 12). Forty-one channels of information were gathered, seven table functions and thirty-four frame functions. Data samples were taken at a rate of 50 samples per second for each channel and stored on magnetic tape.

A cantilever energy-absorbing device was designed for the base isolation system to produce a yield force of 5% of the weight of the structure (4 kips) and to permit lateral deflections of up to ± 6 in. The dimensions of the device are shown in Figure 14. A single device was used in any given test; the device was located under the frame near one end of the table. The device was attached to the frame by an arm connected to one of the cross beams of the base frame. A load cell in the arm allowed the force transmitted to the frame by the energy-absorbing device to be measured directly. The location and connection of the device are shown in Figure 15. The loads cells beneath the bearings and that between the energy-absorbing device and the frame allow the base shear applied to the structure from the table to be monitored continuously and hysteresis loops to be generated for both the bearings and the device.

VI. RESULTS OF THE DYNAMIC TESTING PROGRAM

Four earthquake records were used in the testing program: the El Centro N-S (1940), the Parkfield N65E (1966), the Pacoima Dam S16E (1971), and the Taft (1950) records. These records were time scaled by a factor of $\sqrt{3}$ so that the data could be used to predict the response of full-scale structures. The model was also tested with the records unmodified, a more severe test of the isolation system which allows verification of analytical work in which the model is treated as a full-scale structure.

Maximum displacement and acceleration produced by the shaking table were varied by the SPAN setting which is directly correlated to maximum table displacement. A peak table displacement of ± 5 inches—the limit of the table—corresponds to a SPAN number of 1000; lower span numbers correspond to proportionately lower displacements. The SPAN numbers and corresponding peak table accelerations for each earthquake and for each model condition are summarized in Table 1. The peak table acceleration for the same earthquake and SPAN number may vary considerably since the table motion is displacement controlled and any structure-table interaction may modify the table motion.

Peak accelerations at the various floor levels of the model for the four earthquakes in both real and scaled time are shown in Figures 16(a) through 16(d). The fixed condition which models a conventional foundation shows an amplification which is large for the El Centro and Pacoima scaled records, 4.7 and 2.7 respectively, and which induced horizontal accelerations as high as 2.833g on the fifth floor of the model. Amplification factors for the free condition—which models a completely isolated building—were less than one for all earthquake records. The reductions in peak acceleration effected by the isolation system ranged from a factor of 20 for the Pacoima Dam and El Centro time-scaled records to 5 for the Taft real-time record. Since the frame is a 1/3 scale model, the minimum reduction in a full-scale system would be on the order of that for the Taft time-scaled motion, i.e. 12.5. Accelerations at the floor levels varied only slightly, indicating that the structure was responding to the table excitation with a rigid body motion.

Peak accelerations at each level when the energy-absorbing device was attached were greater than those for the completely isolated case and much less than those for the conventional foundation. It is in fact surprising that the accelerations with the device installed were so little higher than for the completely isolated case. The maximum force transmitted to the frame by the device was roughly 5.0 kips during the most intense earthquake loading and the maximum shear force in the bearings at maximum extension was approximately (0.729 x 4 x 5) 14 kips. The deformed shape of the frame in the case of the rubber bearings only was virtually a rigid body motion and when the energy-absorbing device was included was still very close to a rigid body motion.

The measured accelerations and forces for three intensities of the El Centro record in real time and two in scaled time have been plotted in order to illustrate the response of the frame (Figure 17). The maximum floor accelerations are taken as ratios to corresponding table input acceleration. The response of the structure above the isolation system is virtually a rigid body translation. In real time the response to the El Centro 500 record shows an amplification of acceleration close to 0.48. As the loading was increased through a 750 span setting to a span of 1000, the energy absorber yielded for longer periods; the model structure was thus more completely isolated for more intense loading. This response is reflected in the shift of the acceleration ratios for the more intense earthquakes. For the El Centro 750 record the amplification was approximately 0.37 and for the El Centro 1000 about 0.31. The peak table input acceleration for the El Centro 1000 was 0.711g. The same phenomena is demonstrated for the time-scaled records, although amplification ratios were much lower due to the higher frequency content of the motions. For the time-scaled El Centro 500, a 1.373g maximum table acceleration was recorded with structural response ratios on the order of 0.17.

The displacement at each floor of the model for the fixed-base system was compared to that for the isolation system both with and without the energy-absorbing device installed (Figure 18). The plots are for real and scaled time El Centro motions and represent displacement relative to the shaking table. In real time the structural displacements were just over 3.0 in. for the fully isolated system, indicating an amplification of the maximum table displacement of 1.3. When the energy absorber was installed the displacement was reduced by nearly 1/2 in. For both isolated conditions the recorded displacements represent rigid body motion under both scaled and real time excitations. With the reduced displacement of the scaled motion, however, the device remained fully elastic for most of the test and the reduction in maximum response was thus greater, on the order of 1.4 in.

The response of the fixed-base structure was primarily in the first mode. The displacements thus varied almost linearly with frame floor level, particularly for the time-scaled motion. The maximum relative displacement of the fifth floor for the time-scaled record exceeded that of the isolation system with the energy-absorbing element in place. Although the displacements of the fixed-base model were lower than those of the isolation systems, a large third floor displacement was recorded for the fixed case when subjected to the real-time motion. This large response is the result of a higher mode response to the table input, a mode response not found for the isolated system since the bearing system effectively filters input with a frequency content higher than its fundamental mode.

Time-history plots of the response of the structure to the El Centro 500 motion in real time for the three base conditions are shown in Figures 19(a) through 19(c). Plots of absolute acceleration and relative displacement at each floor level are included as are table acceleration and displacement. The predominant frequencies of the response differ for the various base conditions. For the fixed-base condition, the frequency is nearly 3.0 Hz, while for the bearing system it is only 0.6 Hz. When the device is in place the frequency increases to approximately 0.8 Hz as seen in the time-history plots and as verified by the Fourier transforms of fifth floor acceleration for each case. When the base was fixed the accelerations in the structure were high and increased so greatly from floor to floor that the accelerations for the fourth and fifth floors (Figure 19(a)) are plotted to a different scale. The accelerations for the higher floors of the model increasingly differ in form from the table input and are dominated by the natural frequency of the structure. Model accelerations for the isolated cases were low and all response at all floor levels was similar (see, for example, Figure 19 (c)). When the energy-absorbing element was present the accelerations were slightly greater and the response frequency was increased over the isolated cases.

Displacement relative to the table at all floor levels is shown in Figures 19 for each base condition. As expected, these displacements were for the fixed-base condition virtually zero at the base. However, response was amplified at the higher floors of the model and displacement became significant.

Fourier transforms of fifth floor acceleration are given in Figure 20 for each base condition in response to the El Centro 500, 750, and 1000 ground motions. The predominant response frequencies generated in the system can be estimated from these transforms. For the fixed case the highest response is around 2.8 Hz although there was some participation for almost the entire measurable frequency range. On the other hand the energy-absorber and free systems responded at the frequency determined by the isolation system since except at actual structural frequencies the system filters response.

The time history of absorber force as recorded by a load cell integrated in the arm connecting the cantilever to the base of the structure indicates maximum peak forces of approximately 3.5 to 4.0 kips, in the region of the yield force of the device. As with all plots of energy absorber force, when the peaks of the curve are flat the absorber is yielding; these flat peaks can generally be related to high displacements of the base relative to the shaking table.

In Figures 19(c) through (e) the time-history of response of the system with the energy-absorbing element installed and subjected to the El Centro 500, 750 and 1000 motions in real time are plotted in order to demonstrate the effect of different magnitudes of the same earthquake on the seismic isolation system. Maximum peak forces for the energy absorber increase from 3.85 kips for the El Centro 500 to 4.81 for the El Centro 1000, a relatively low increase that indicates significant plastic action in the cantilever. The maximum table displacement and acceleration ratios of the El Centro 1000 to the El Centro 500 are 1.99 and 2.24, respectively.

Although the form of the time history-records for the three magnitudes of the El Centro record is slightly altered when the intensity of the record is increased, the primary effect of raising the intensity is a linear increase in displacement of the floors of the model with respect to the shaking table. For example, the ratio of maximum displacements under the El Centro 1000 motion to those under the El Centro 500 motion is 2.05. The reduction of stiffness of the isolation system when yielding occurs and hence the reduction in restoring force is thus compensated for by energy dissipation through yielding of the device.

Accelerations did not vary linearly, but ratios decreased with increasing intensity of motion. The ratio of maximum base acceleration for the El Centro 1000 to that for the El Centro 500 is 1.4, significantly lower than the 2.0 input ratio, due to the yielding of the cantilever device which limited the base shear transmitted into the structure and hence also limited absolute acceleration. This was also clearly demonstrated in Figure 17.

Although not necessarily indicative of prototype performance, response of a model system in real time is a much more severe test of an isolation system. Time-history plots of absolute acceleration, relative displacement, and energy-absorbing force for the Pacoima Dam, Taft, and Parkfield records in real time are given in Figures 21 through 23. The maximum table input displacement for each is roughly equivalent to that for the El Centro 500 record.

The Pacoima Dam record is the most rigorous test of the isolation system due to a sequence of two or three large input displacements at the beginning of the record, a sequence which produces one extremely high cycle of relative structural displacement; an amplification of displacements factor of 2.29 was recorded for the Pacoima Dam real-time record. For an isolation system in which rubber bearings are incorporated relative base displacement is the critical response. High table accelerations such as occur later in the Pacoima Dam record negligibly affect structural response since most of the high-frequency content is filtered by the system. Maximum absolute accelerations occur simultaneously with maximum relative displacement due to response in the fundamental mode of the isolation system, a phenomena common to all earthquake records used in this test series. The energy absorber plot reflects relative displacement response and a large amount of cantilever plastic action.

Neither the Taft nor the Parkfield records gave rise to the dramatic response of the isolation system to the Pacoima Dam record. Peak structural displacement and amplification ratios were similar to those for the El Centro record. Accelerations were directly correlated to relative base displacement; for both records the cantilever device extended into the plastic region. Base relative displacement and acceleration, table displacement and acceleration, and corresponding ratios are given in Table 1.

VII. ESTIMATE OF EQUIVALENT VISCOUS DAMPING

Hysteresis curves of device response in two four-second portions of the El Centro records beginning at 6.00 seconds and at 22.25 seconds (chosen to represent high excitation and low excitation, respectively) for the El Centro 500, 750, and 1000 motions are shown in Figure 24. For the high excitation portion of the record, during which substantial plastic action occurred, energy dissipation through the energy-absorbing device hysteresis increased with increasing span ratio. Although this relation clearly cannot be linear since the action of the cantilever device is elastic-plastic, relatively more energy is dissipated at higher levels of force. Maximum absorber force was 4.8 kips; initial yielding occurred at 3.5 kips. A slight asymmetry due to the small offset of the loading pin is noticeable in the curves, an effect that was mentioned in connection with the static testing of the device. For the lower, excitation response was virtually elastic although the peak force was 3.0 kips. Hysteresis curves were extracted for the bearings for the same earthquake records and time periods (Figure 25). The curves for the bearings are drawn to a different scale. The bearings have roughly the same stiffness as does the cantilever when elastic. A substantial amount of damping was produced by the bearings.

Stiffness and energy dissipated were found for both the device and the bearings from the largest loop in each plot. Dissipated energy is plotted against ductility factor in Figure 26. Since the elastic displacement of the cantilever was taken to be 1.00 in., the ductility factor may be read as displacement in inches.

Equivalent natural undamped frequency ω and equivalent viscous damping ratio ξ determined by correlating dissipated energy per cycle are given in Table 2. The formulae used to calculate these quantities are

$$\omega = \frac{K_a + K_b}{M}^{1/2}$$

$$\xi_e = \frac{A_a + A_b}{2\pi (K_a + K_b) y^2} \frac{\omega}{\Omega}$$

where y is the root mean square displacement for forward and backward maxima on the largest loop, M is the total mass of the structure and Ω is the frequency of response. The terms K_s and A_s refer to stiffness and energy dissipated of the device and the bearings. As displacement increased, the natural fundamental frequency of the system decreased and, in the range of values tested, equivalent damping increased (Figure 27). A flat peak should occur in the curve at a ductility factor just over 5 (or a displacement of just over 5 in.). The estimates of equivalent damping derived from these data are high with respect to those usually assigned to conventional steel and concrete structures. Their variation results from the difference between hysteretic and viscous damping. If the response of the device were idealized as elasto-plastic, its energy absorption would vary linearly with displacement, whereas an ideally viscous system varies quadratically, and thus at some high displacement must dissipate more energy.

VIII. CONCLUSIONS

The accelerations experienced by a structure when subjected to earthquake ground motion are, even in the absence of an energy-absorbing device, effectively limited by the natural rubber bearing base isolation system described here. The motion of a building on such a system is constrained to the rigid-body motion of the superstructure; response of the structure is nowhere amplified. The relative displacements across the bearings are, however, great and the stiffness of the isolated structure particularly low. When the tapered steel energy-absorbing devices are combined with the bearings, these difficulties are largely overcome with no significant loss of the beneficial effect of the bearings in isolating buildings from the damaging effects of ground motion.

The initial stiffness of the cantilever devices restrains the motion of a structure under low-intensity loading such as that produced by wind, and the base shear provided by the devices restricts displacements of the structure at the bearings during more intense ground motion. The bearings and devices together act to introduce a high degree of hysteretic damping to the response of the structure—as much as 15% equivalent viscous damping is introduced for large oscillations. The relative displacements at the bearings are greatly reduced by the cantilever devices, a particularly important response for the stability of the bearings. The structural accelerations, although slightly higher than when no devices are present, remain well below those of the ground motion. The building moves on the bearings in a virtually rigid-body motion as it does when on the bearings alone; internal equipment and components are thus protected.

The results of the static and dynamic tests of the cantilever device demonstrate that the devices can withstand very many cycles of earthquake ground motion without significant deterioration in response. It is accepted that a structure must undergo some plastic deformation to dissipate the energy transmitted through the foundation during seismic loading and thus to survive the ground motion. The cantilever devices are designed primarily to absorb such action; all plastic action is concentrated in the devices and a structure will be undamaged by the ground motion. Since the cantilever elements will for a given high-intensity ground motion have undergone many cycles of plastic action, they may need to be replaced.

Several isolation systems that have been proposed do not incorporate a mechanism whereby the large relative horizontal displacements that can occur in isolation systems under nondamaging ground motion and service loads can be reduced. Such large horizontal displacements could also affect the efficacy of bearings under intense ground motion. The system described here overcomes these shortcomings; a safe, simple, and virtually maintenance-free system has been realized. The system can be adapted readily to full-scale construction; no special design or construction problems are anticipated. By isolating structures on rubber bearings with the cantilever energy-absorbing devices, a practical and economical design method which increases the safety of structures and better protects internal equipment and components is realized.

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TABLE 1
PEAK TABLE AND BASE DISPLACEMENTS AND ACCELERATIONS FOR ISOLATED MODEL WITH DEVICE INSTALLED

Earthquake	Table Displ. (in.)	Base Displ. (in.)	Displ. Ratio	Table Accel. (g)	Base Accel. (g)	Accel. Ratio
EC 500 e/a	2.398	22.707	1.13	0.318	0.154	0.48
PC 500 e/a	2.587	5.930	2.29	0.650	0.230	0.35
TA 500 e/a	2.520	3.009	1.19	0.298	0.163	0.55
PK 500 e/a	2.374	2.701	1.14	0.222	0.155	0.70

TABLE 2
EQUIVALENT VISCOUS DAMPING RATIOS FOR LARGEST CYCLE OF FOUR-SECOND PERIOD OF RESPONSE TO EL CENTRO GROUND MOTIONS

HIGH REGION

	y in.	Ω rad/s	K_a k/in.	K_b k/in.	A_a k-in.	A_b k-in.	ω rad/s	ξ_e %
EC 500	2.13	4.83	1.77	2.93	12.0	3.9	4.77	11.7
EC 750	3.42	4.33	1.19	2.73	28.35	10.35	4.35	13.5
EC 1000	4.71	3.93	0.95	2.40	49.8	19.65	4.02	15.2

LOW REGION

	y in.	Ω rad/s	K_a k/in.	K_b k/in.	A_a k-in.	A_b k-in.	ω rad/s	ξ_e %
EC 500	0.61	6.61	3.49	3.26	0.45	0.60	5.71	5.7
EC 750	0.74	6.61	3.16	3.25	1.30	1.20	5.56	9.5
EC 1000	0.99	6.61	3.02	3.11	1.70	1.38	5.44	6.7

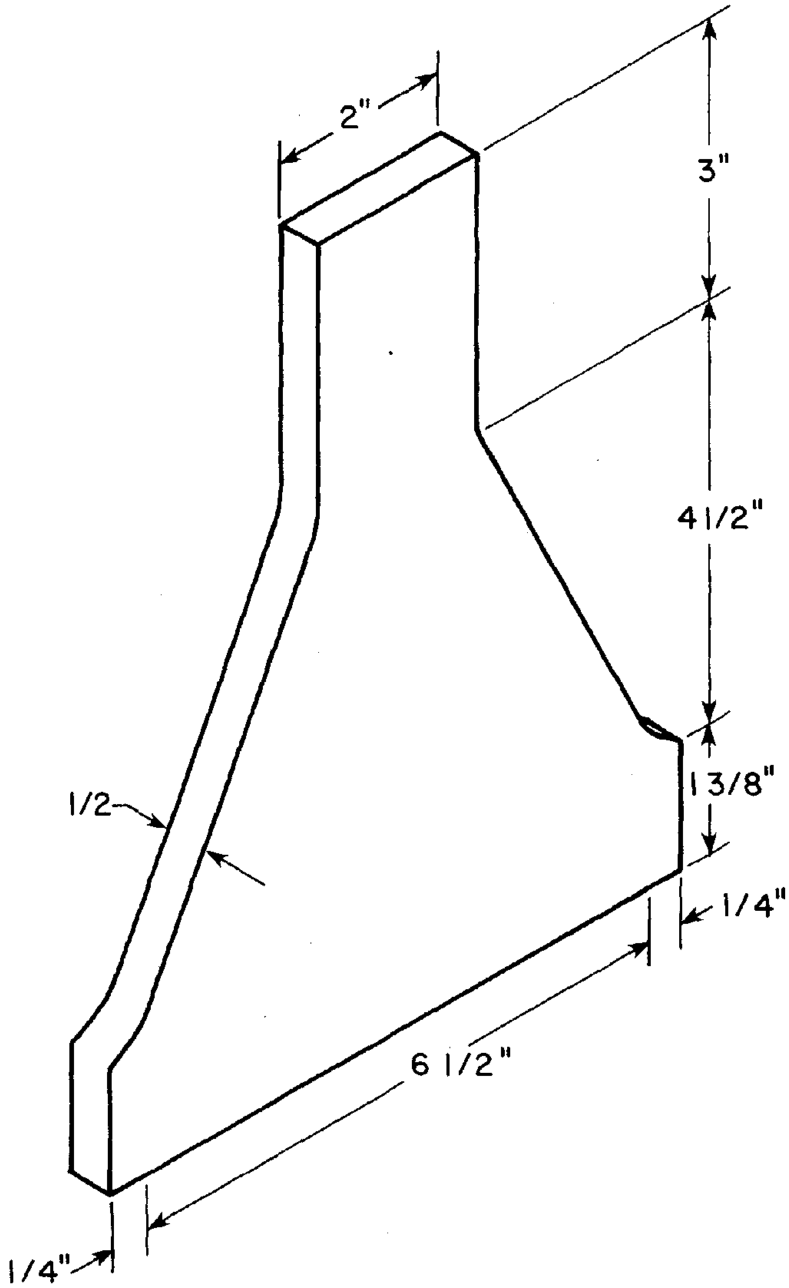

Figure 1 Dimensions of Cantilever Device

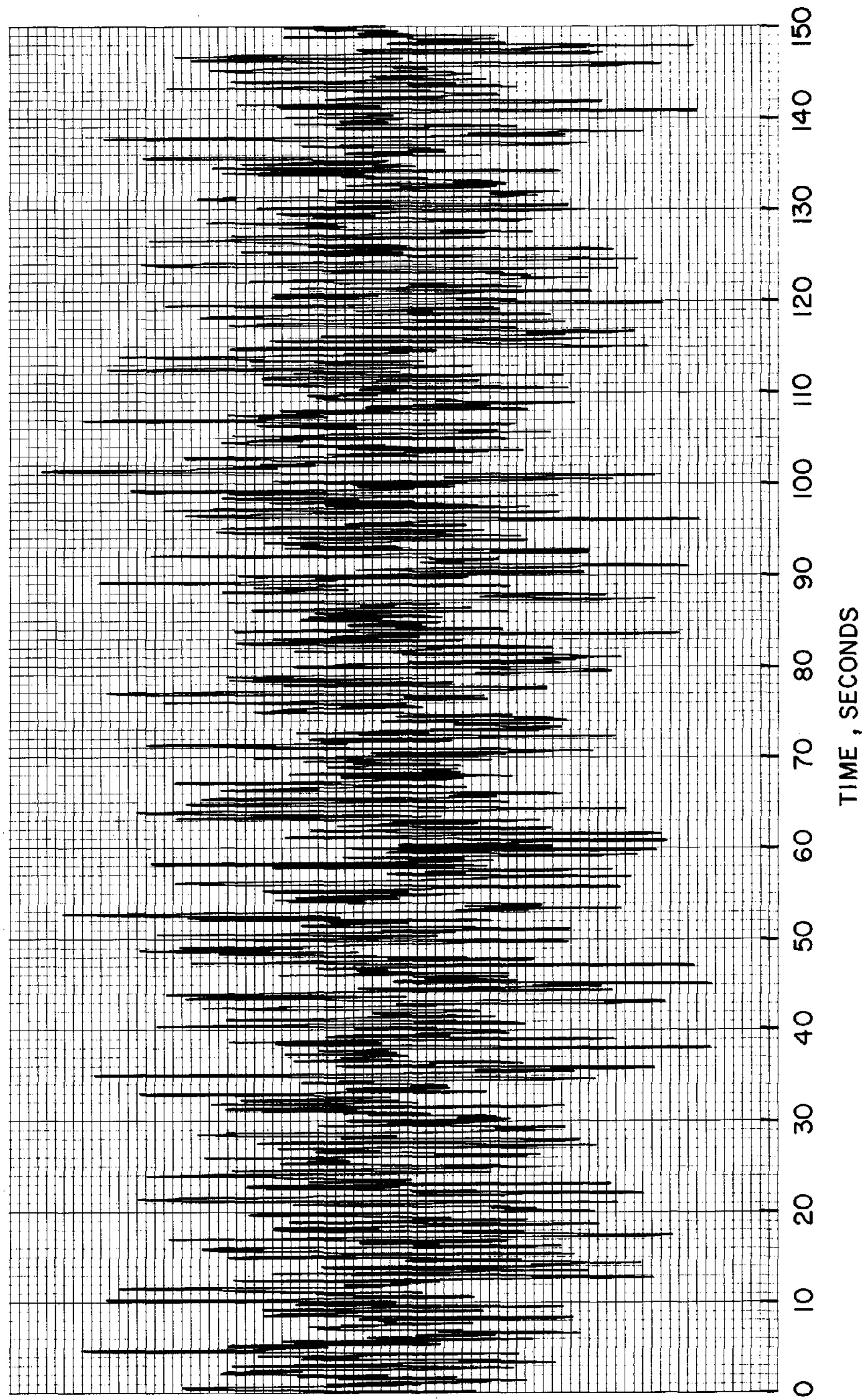

Figure 2 Random Input Function

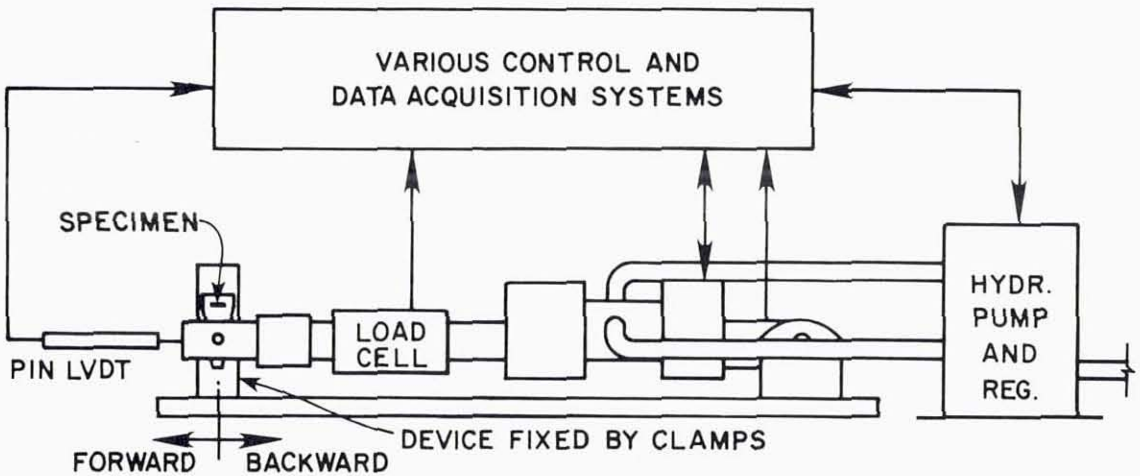

Figure 3 Experimental Set-Up

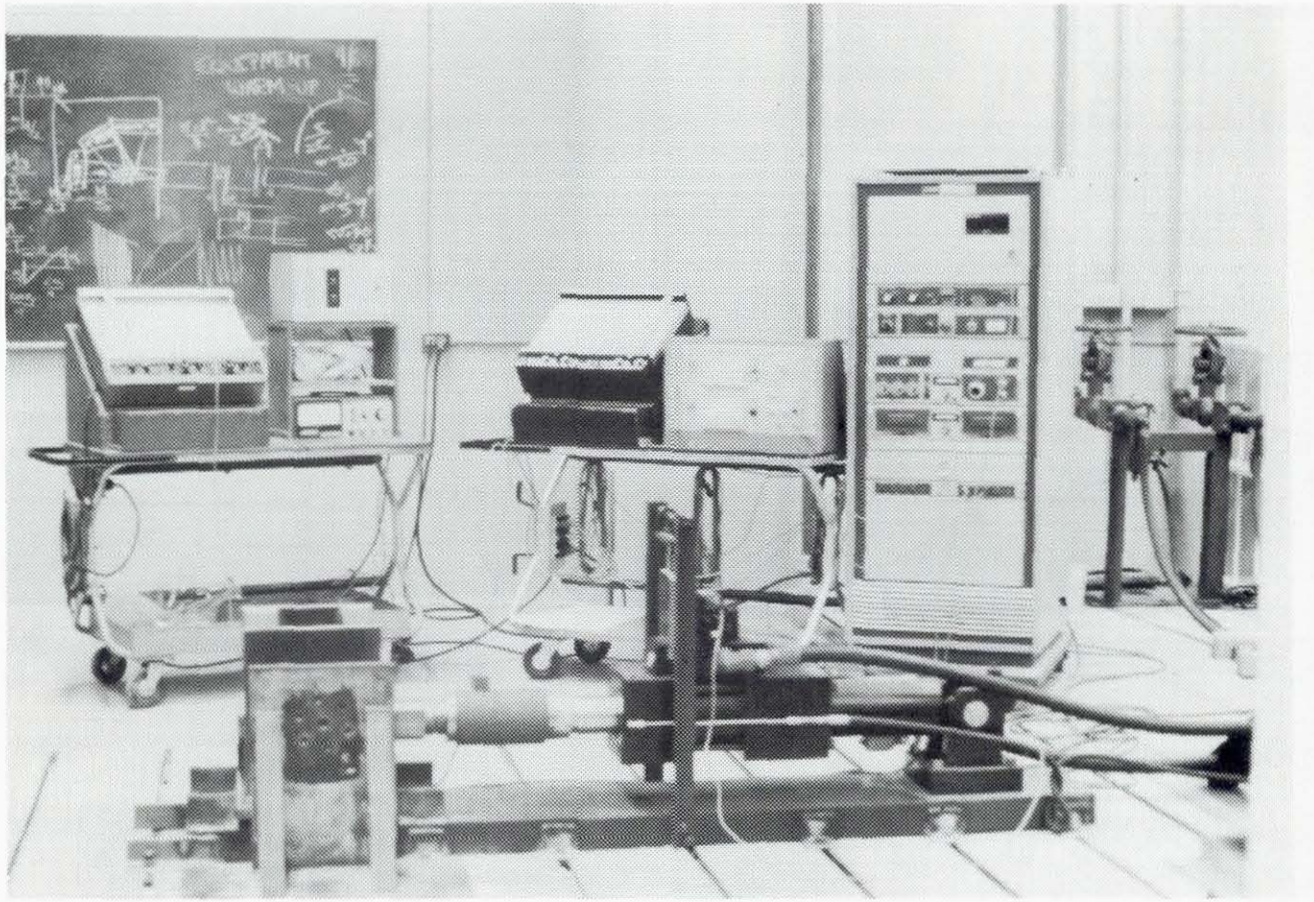

Figure 4 Hydraulic Ram and Data Acquisition System

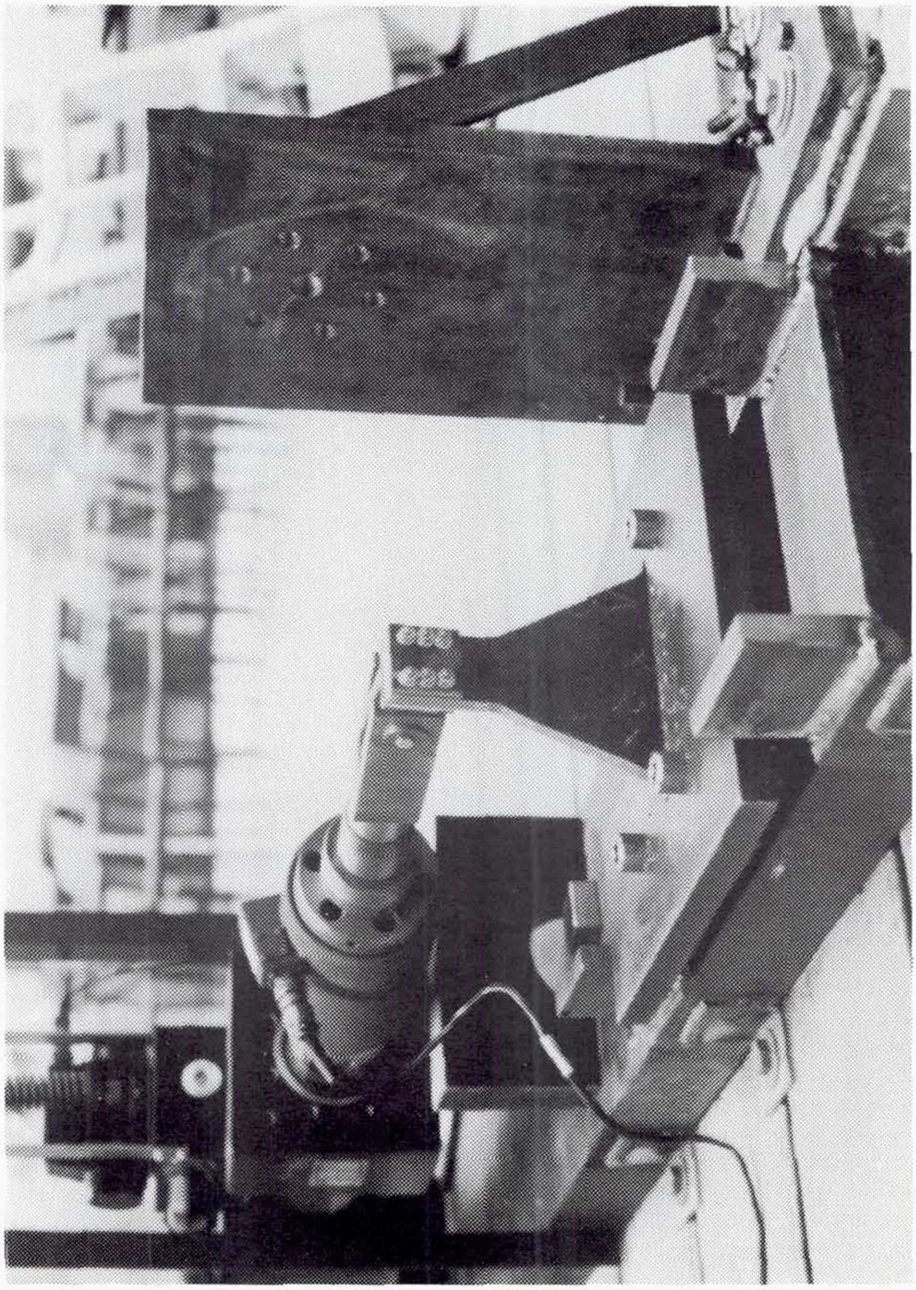

Figure 5 Testing of Cantilever Device

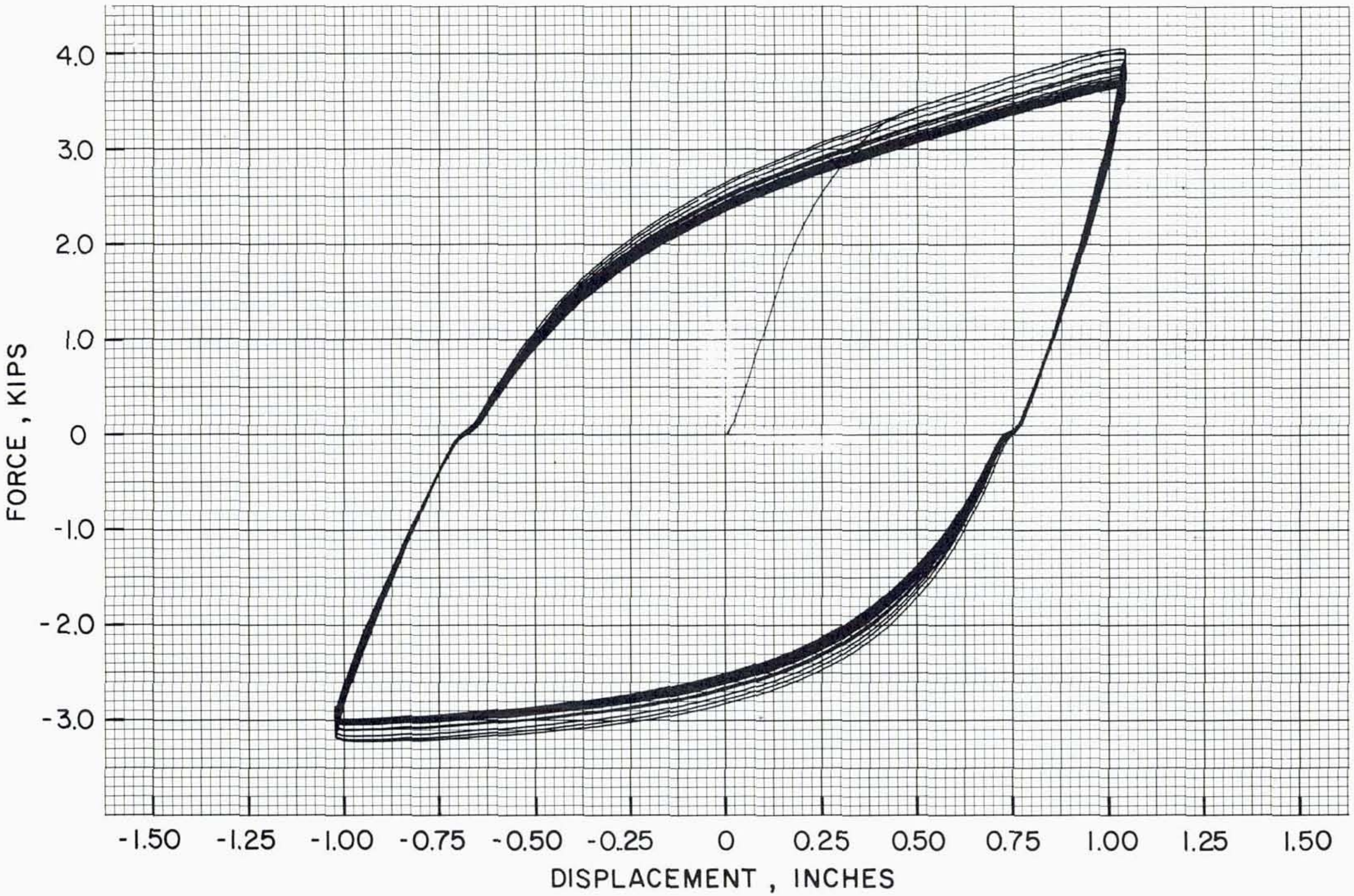

Figure 6 Hysteresis Loops 6 to 206 for Cantilever Device 102

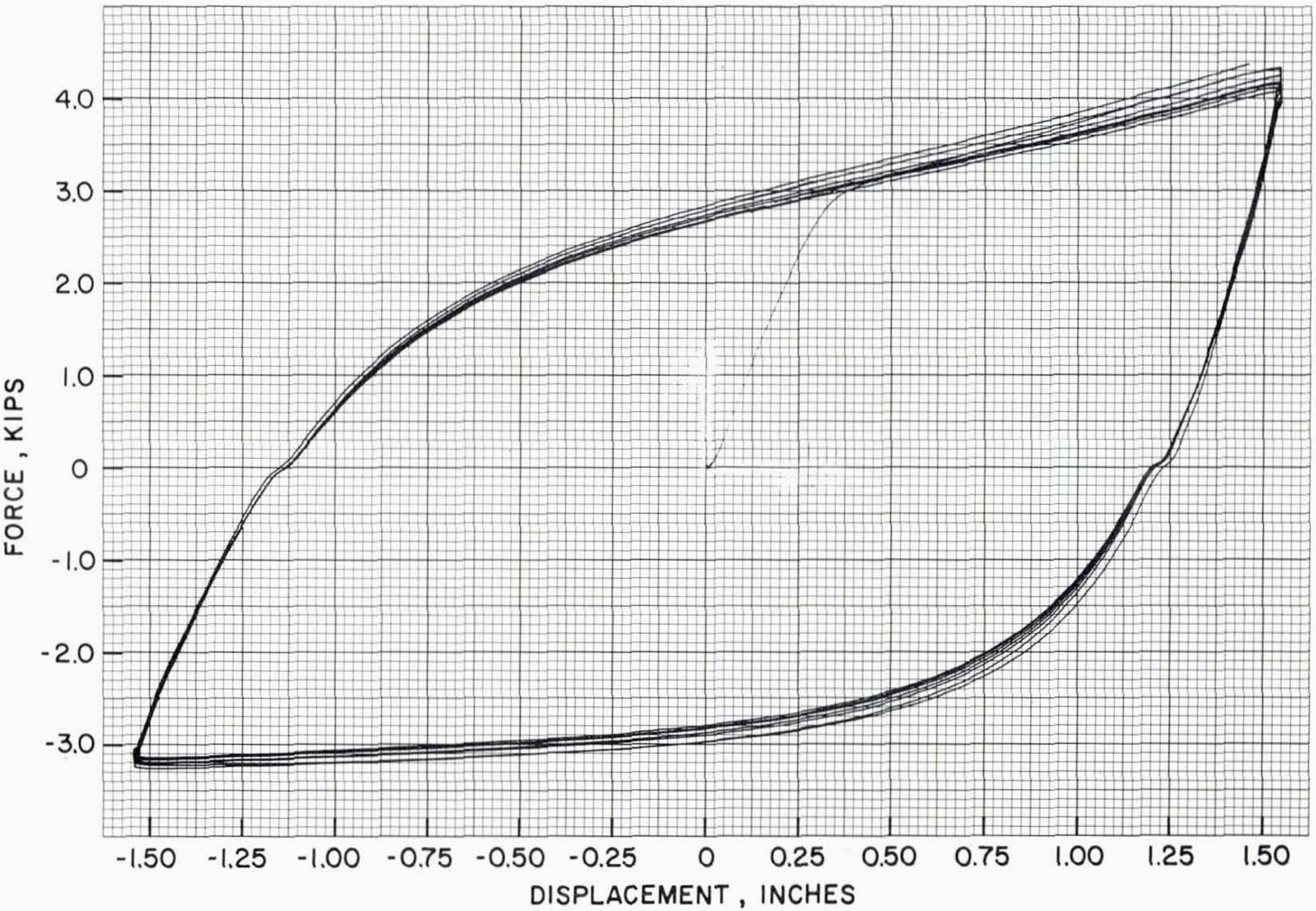

Figure 7 Hysteresis Loops 210 to 260 for Cantilever Device 102

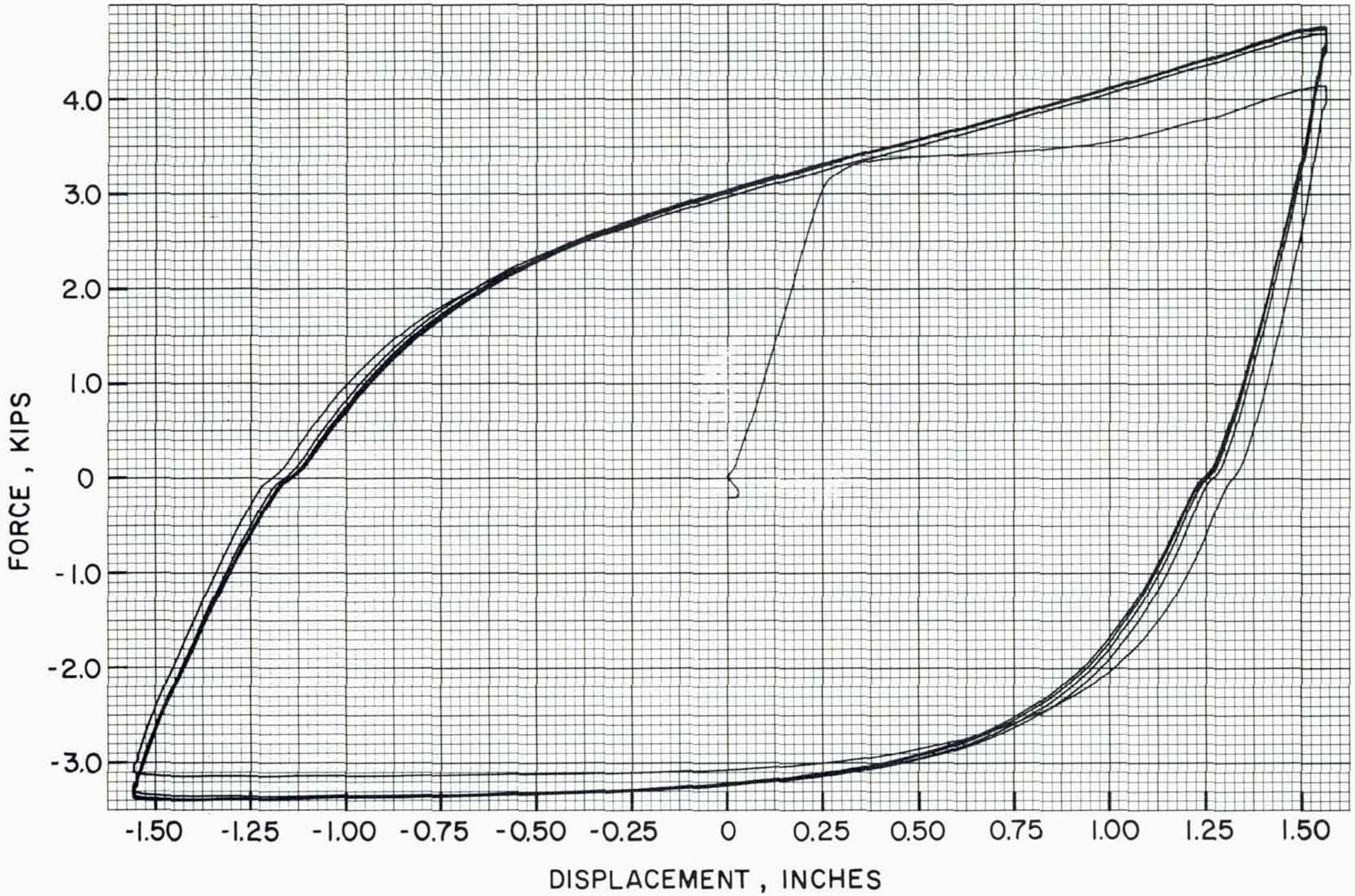

Figure 8 Hysteresis Loops 1 to 5 for Cantilever Device 103

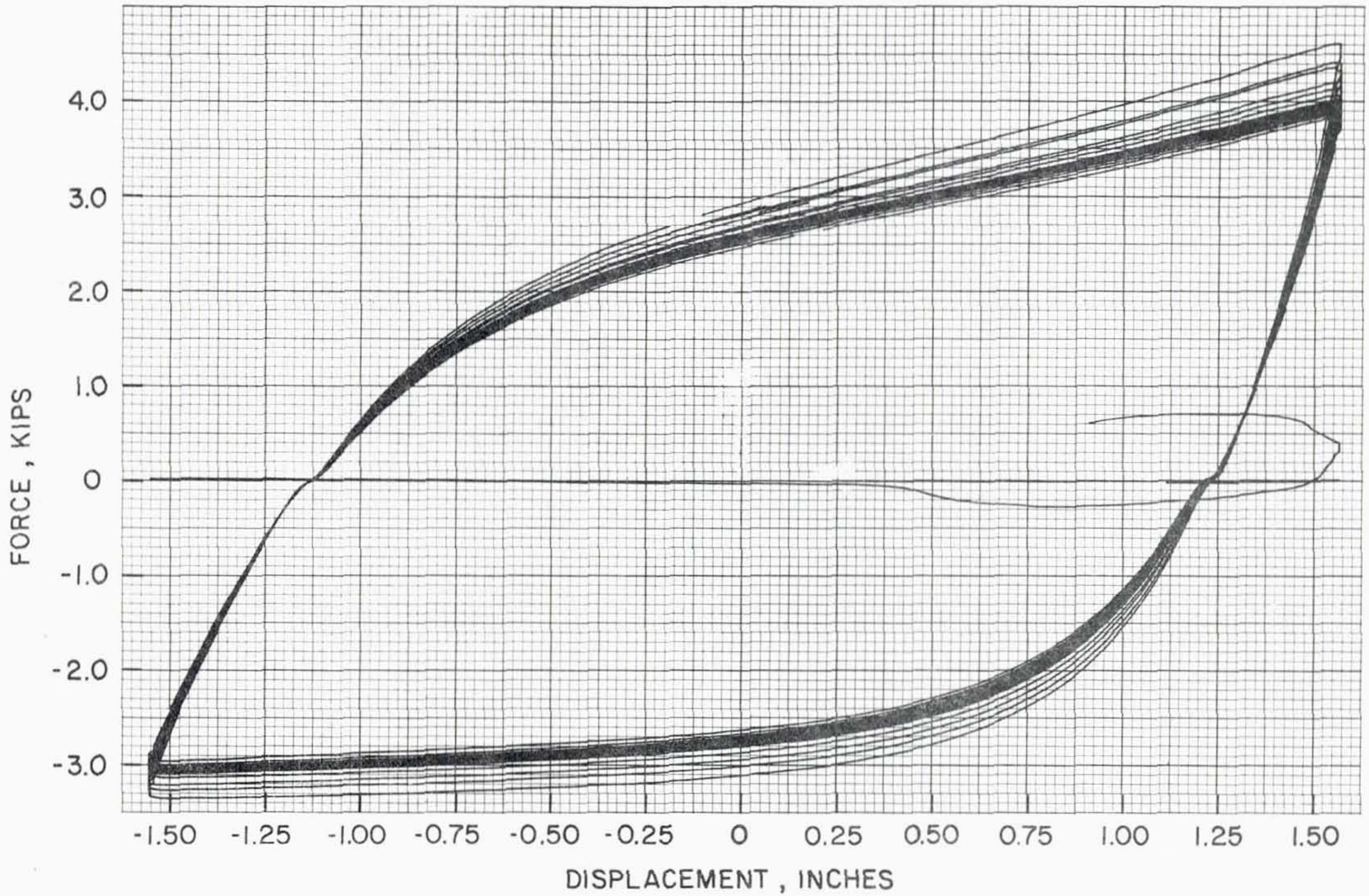

Figure 9 Hysteresis Loops 11 to 161 for Cantilever Device 103

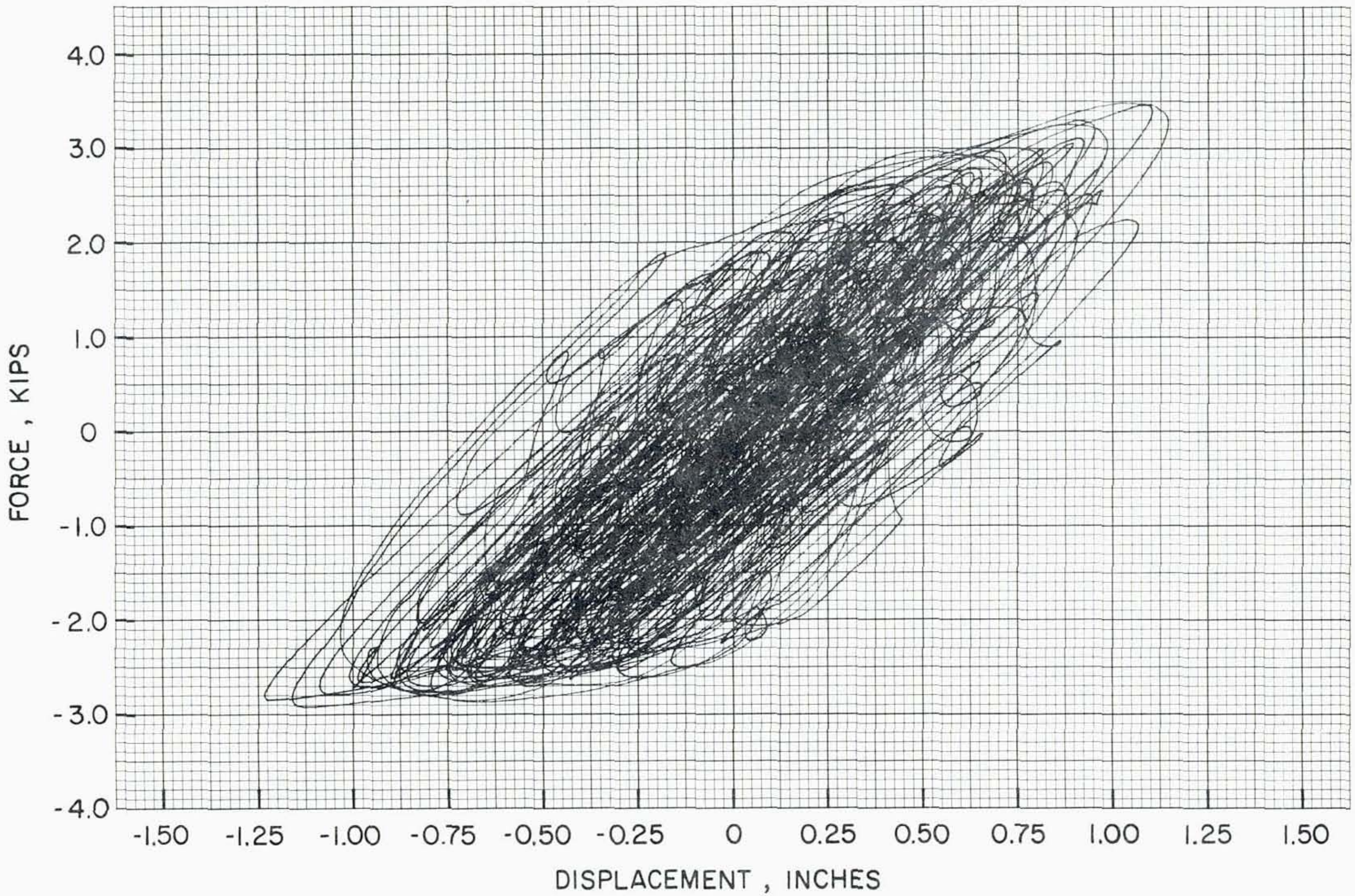

Figure 10 Hysteresis for Device 105 for 100 Seconds from 0 Minutes

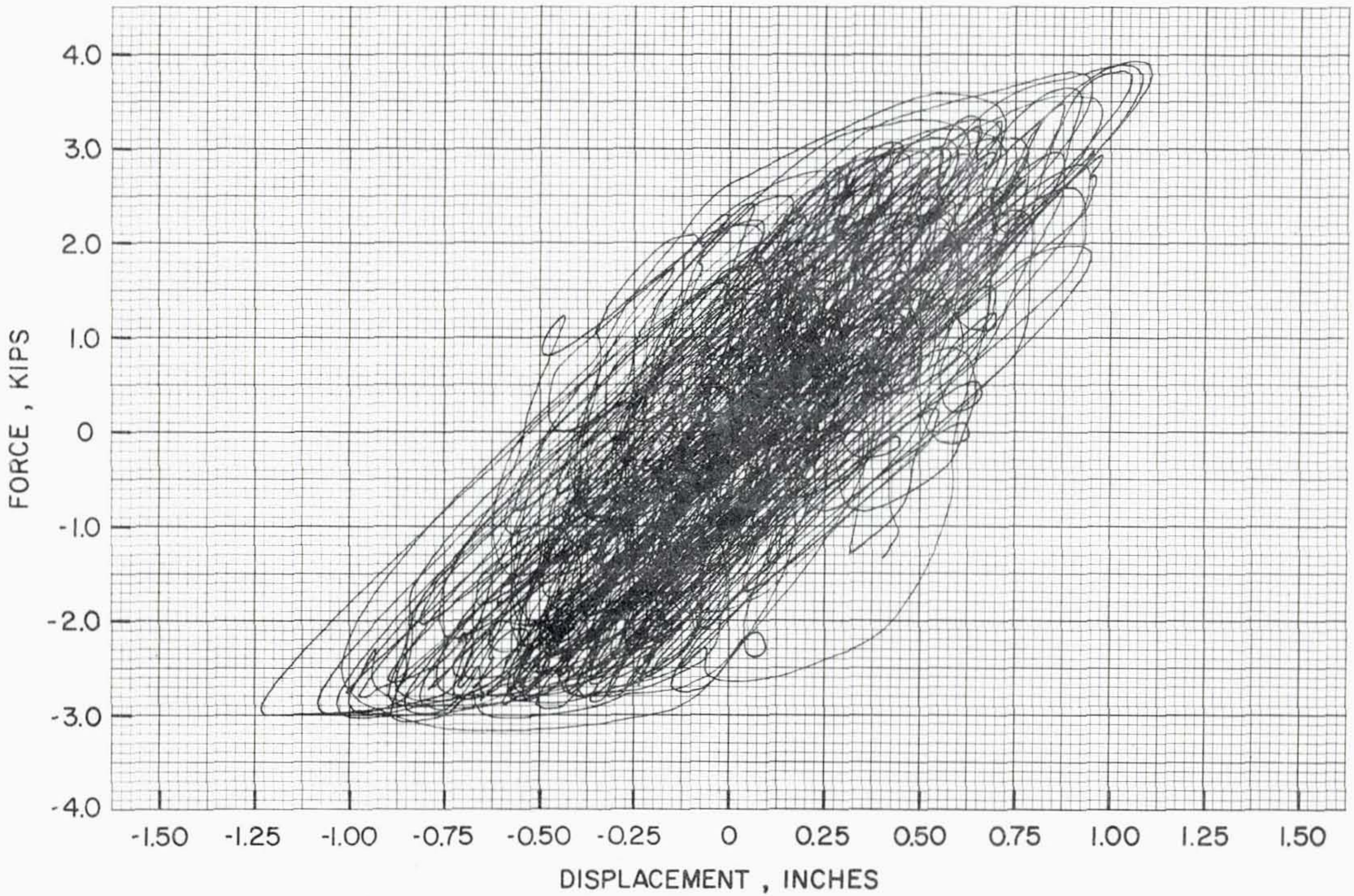

Figure 11 Hysteresis for Device 105 for 100 Seconds from 20 Minutes

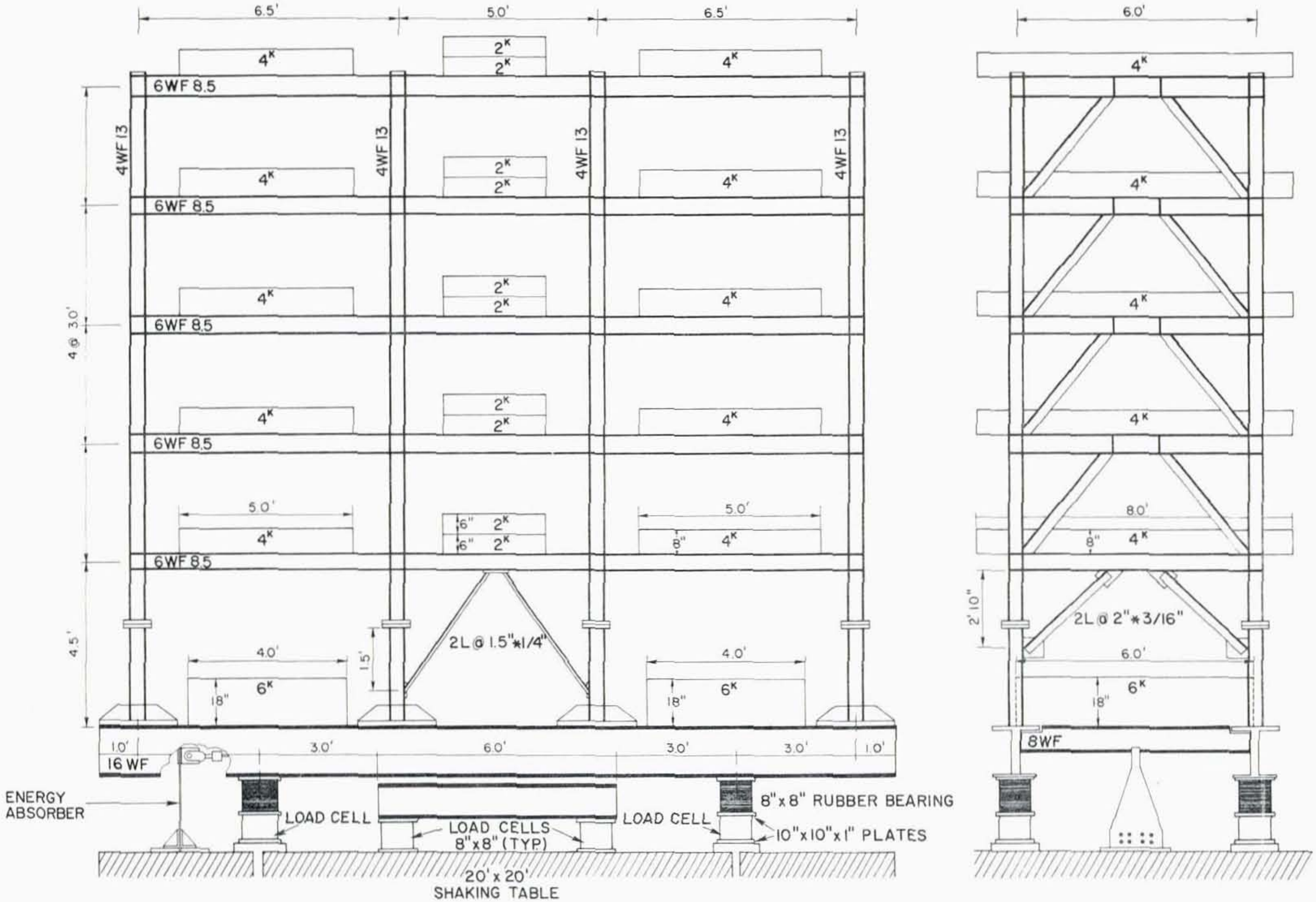

Figure 12 One-Third-Scale Structural Model—Dimensioning and Isolation System

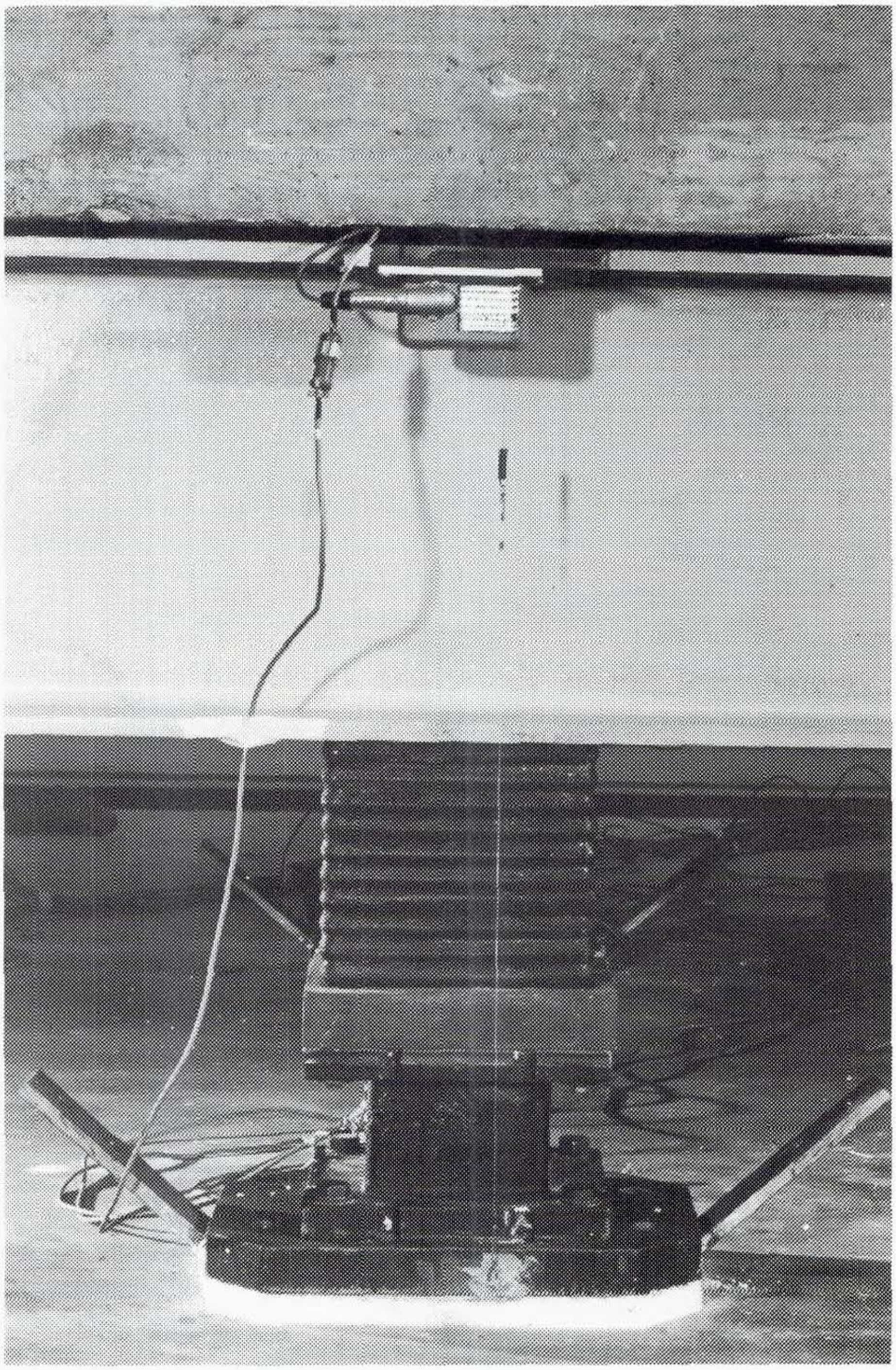

Figure 13 Isolation Bearing Installed under Frame on Shaking Table

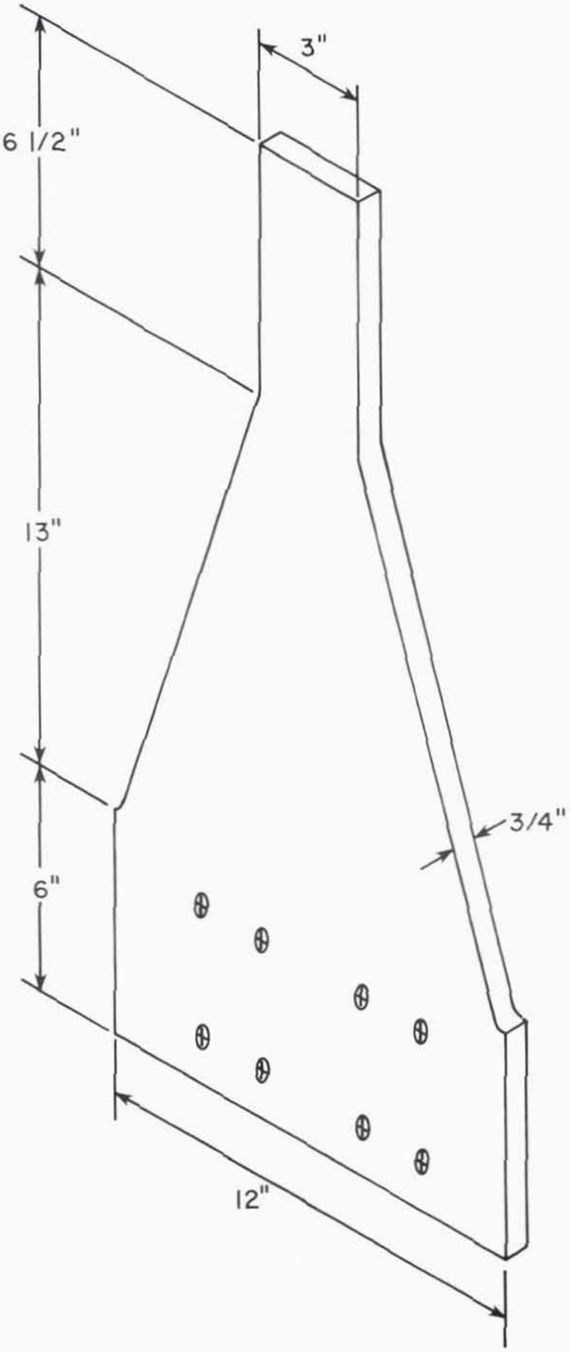

Figure 14 Dimensions of Cantilever Device for Shaking Table Tests

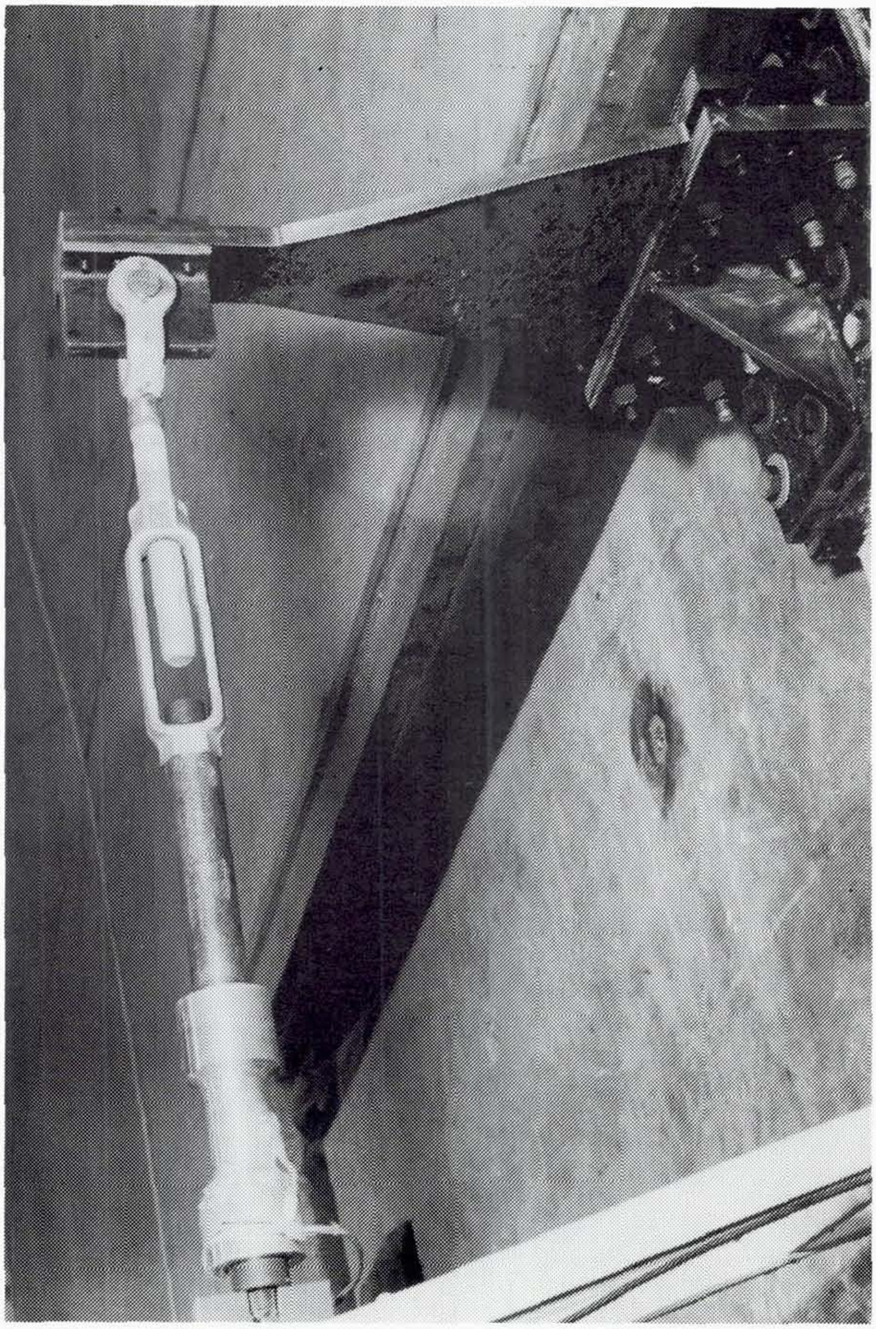

Figure 15 Location and Connection of Cantilever Energy-Absorbing Device

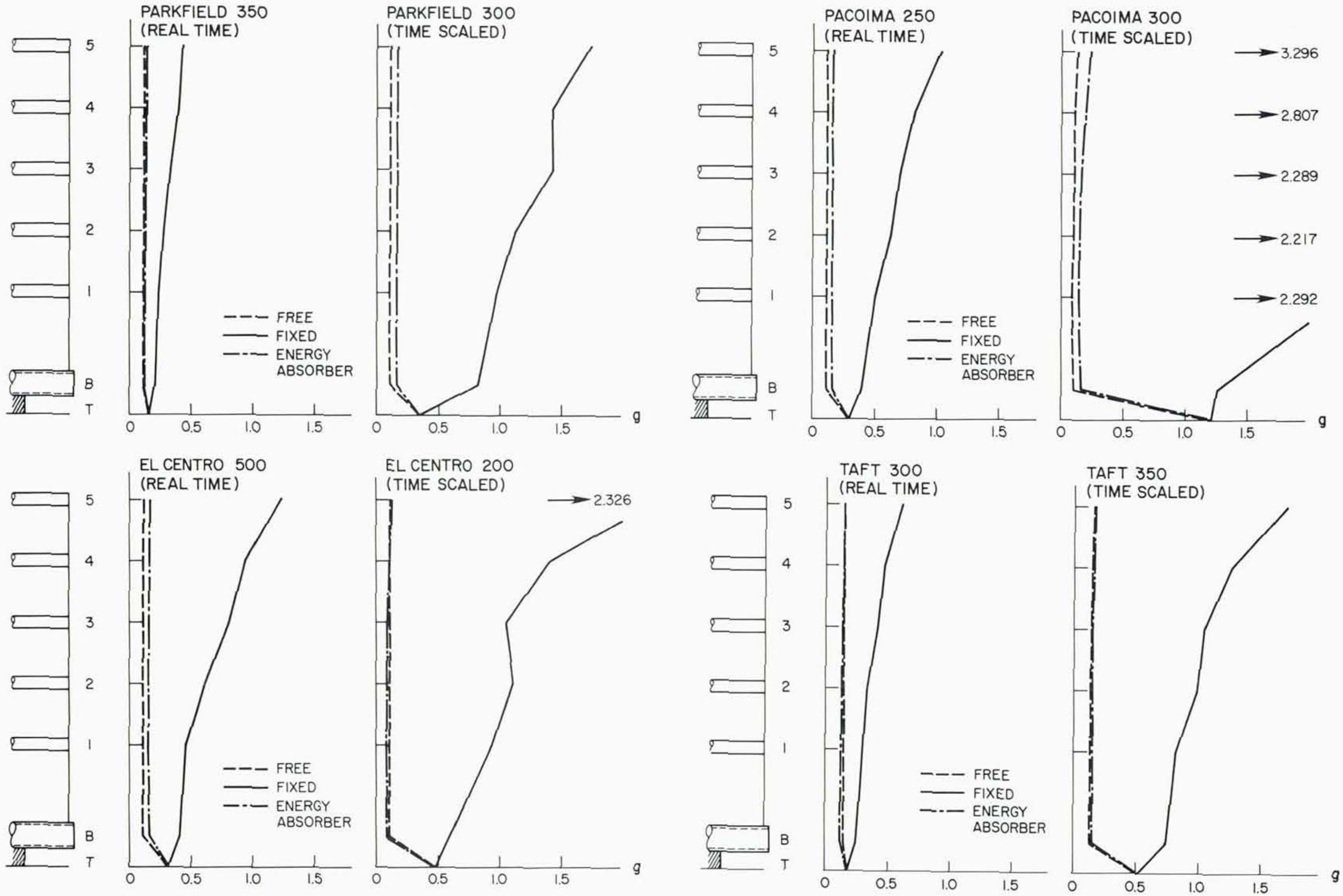

Figure 16 Peak Acceleration at Each Floor for Each Base Condition

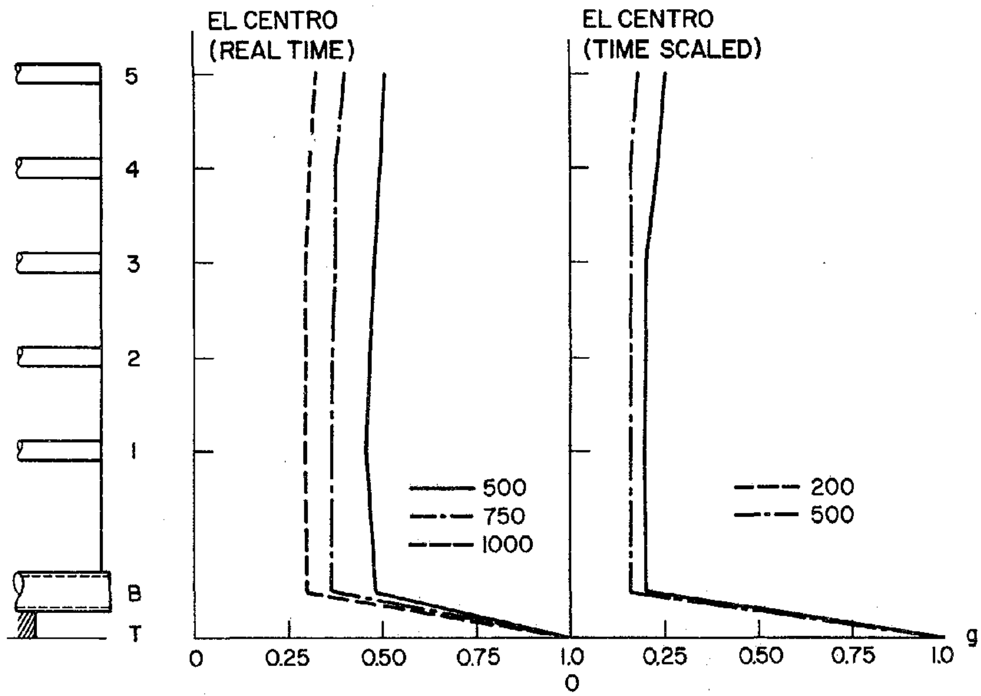

Figure 17 Ratios of Peak Acceleration for El Centro Ground Motion

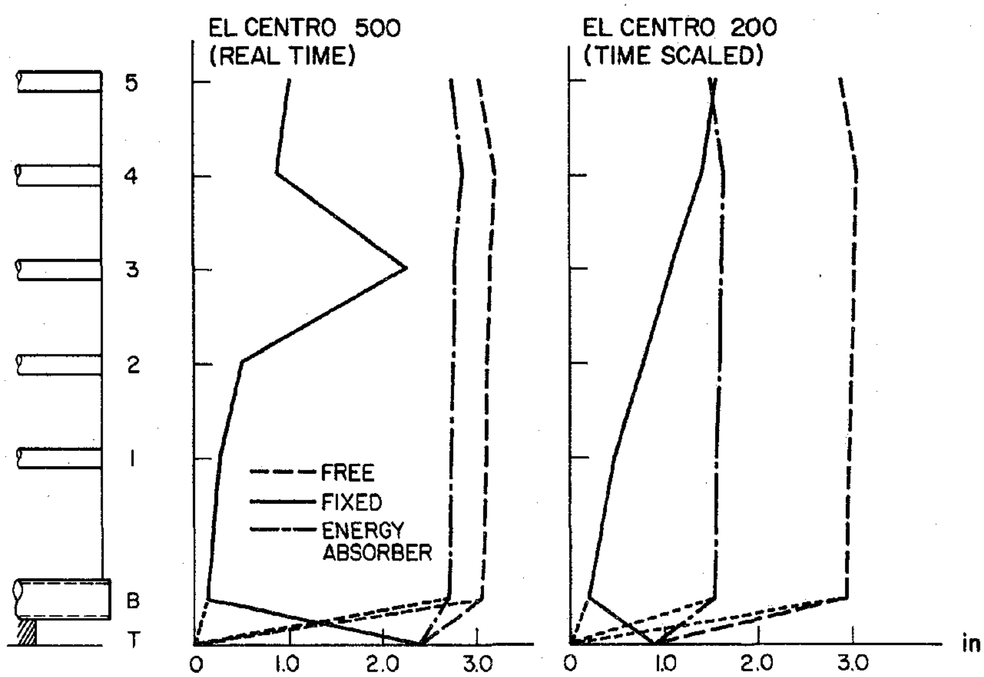

Figure 18 Relative Peak Displacement for Each Base Condition: El Centro Ground Motion

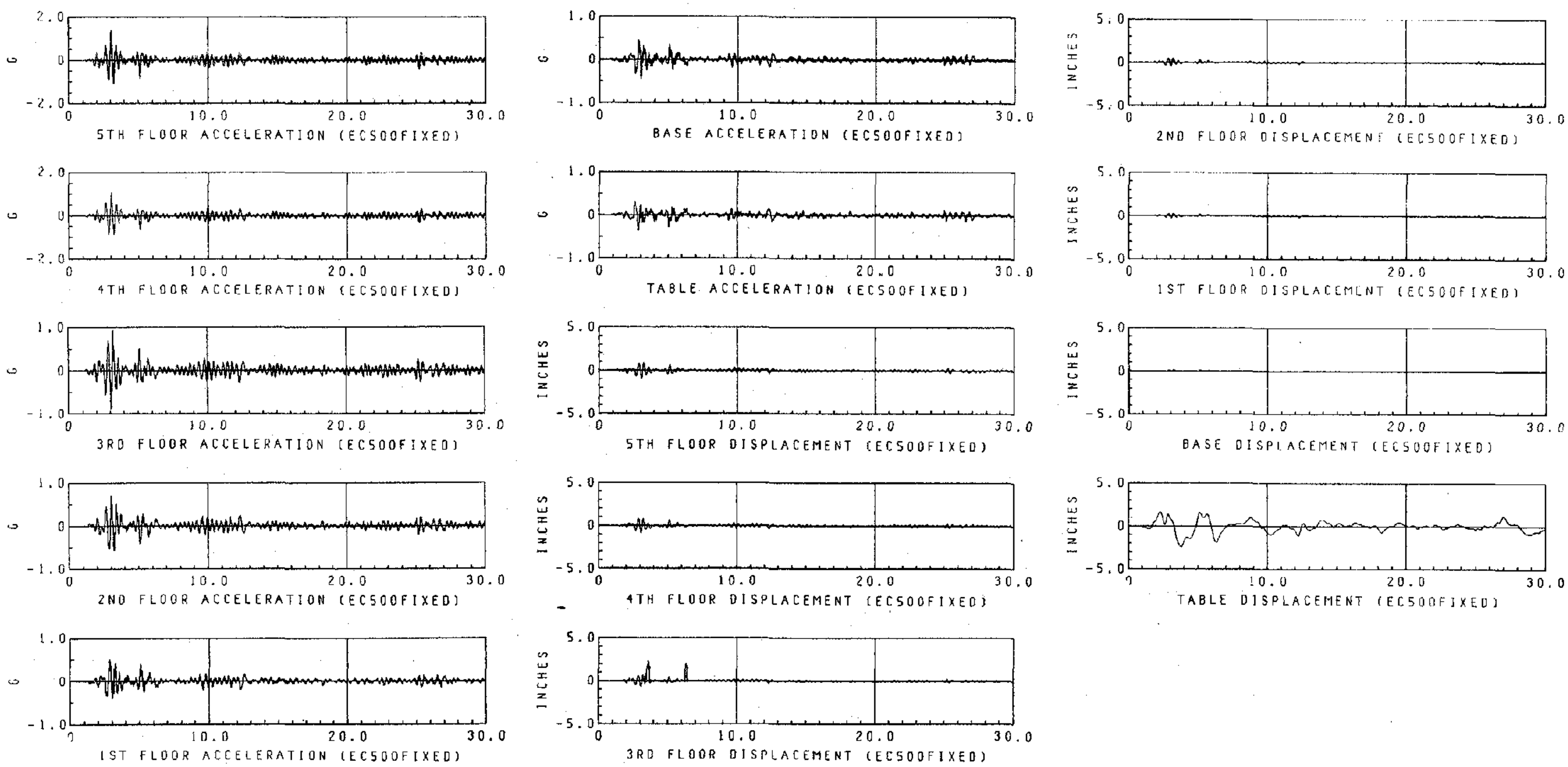

Figure 19(a) Acceleration and Displacement Time Histories: El Centro 500 Ground Motion, Fixed Base

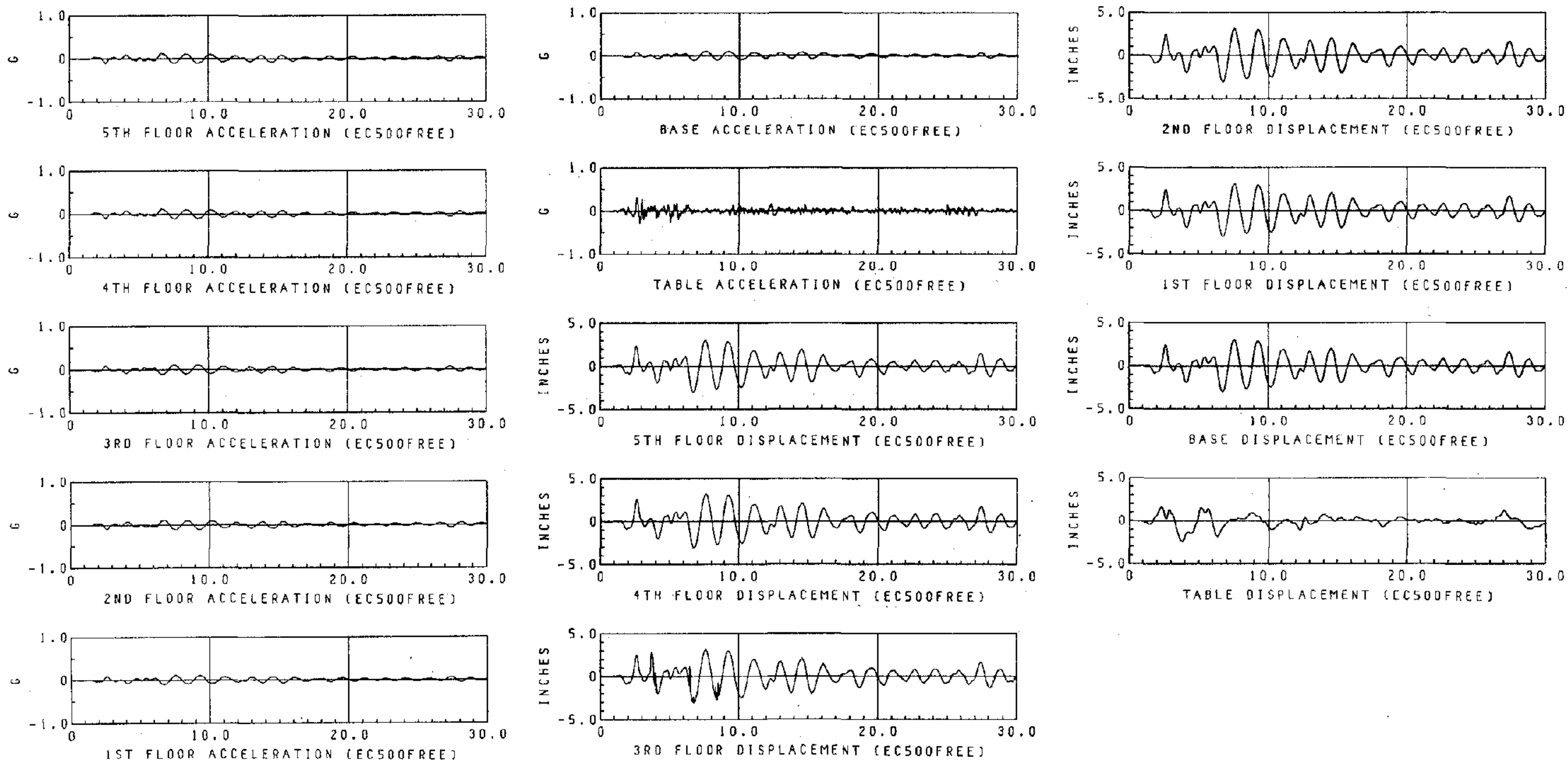

Figure 19(b) Acceleration and Displacement Time Histories: El Centro 500 Ground Motion, Free Base

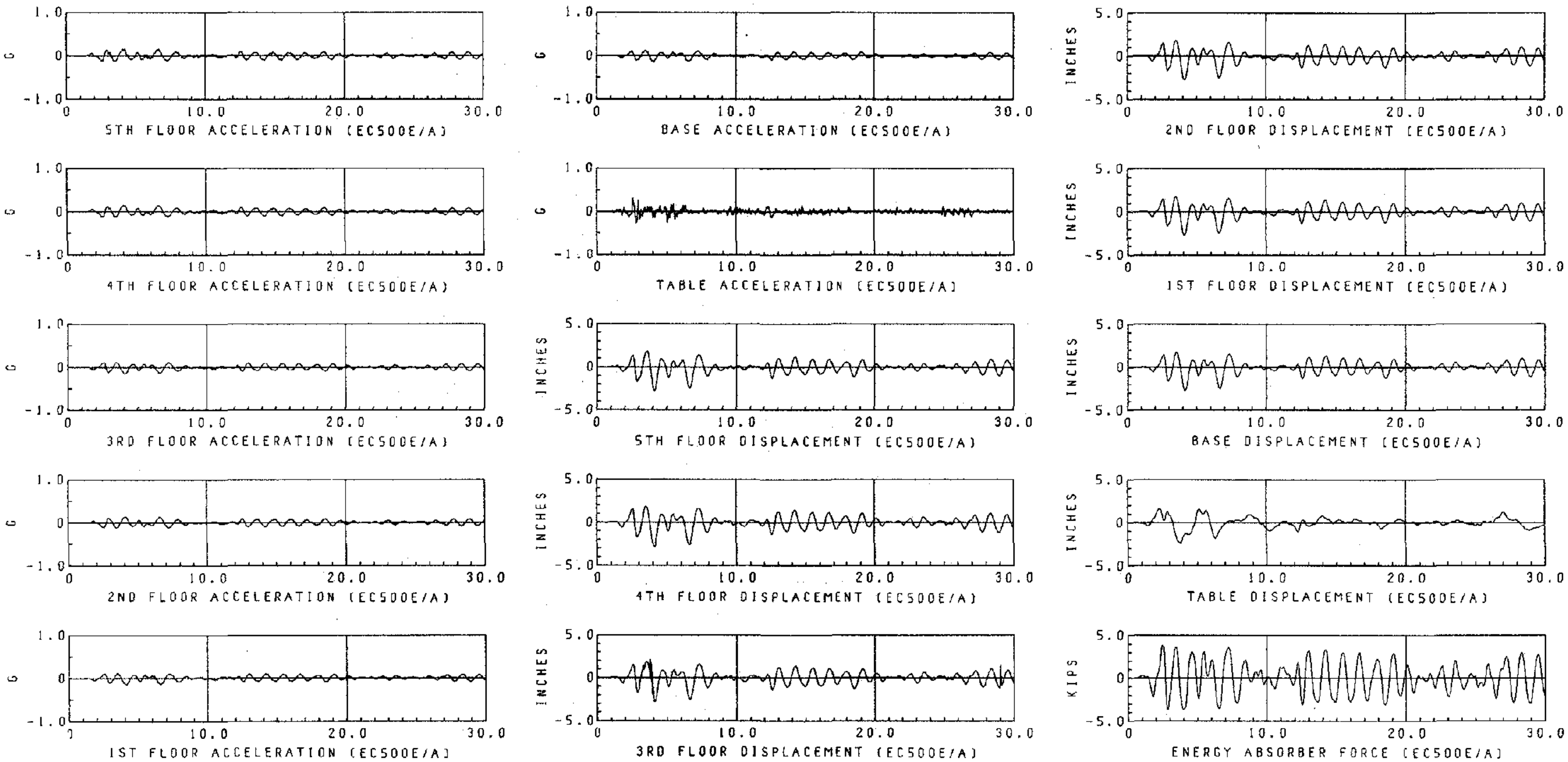

Figure 19(c) Acceleration and Displacement Time Histories and Energy Absorber Force: El Centro 500 Ground Motion, Energy Absorber Base

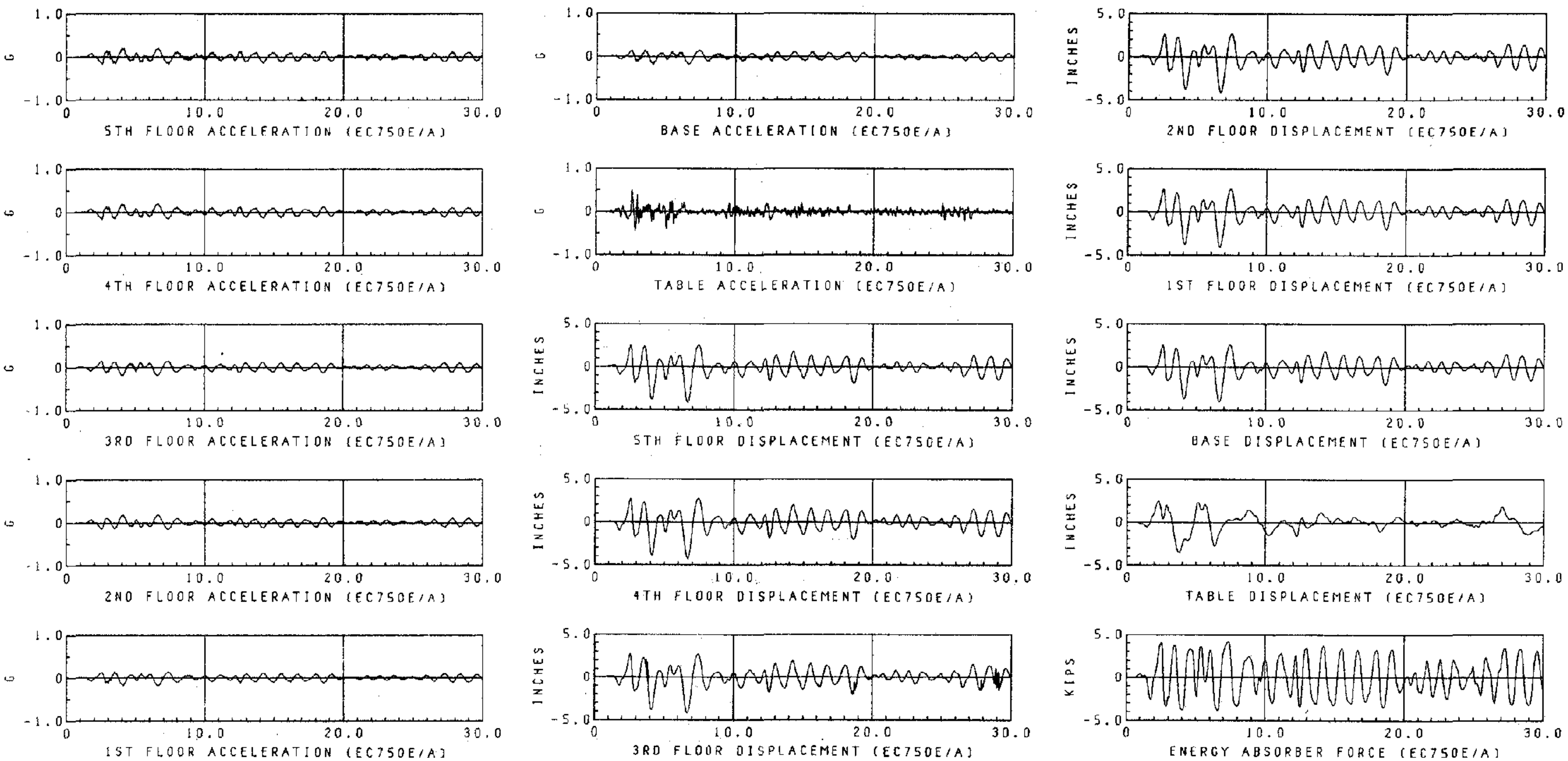

Figure 19(d) Acceleration and Displacement Time Histories and Energy Absorber Force: El Centro 750 Ground Motion, Energy Absorber Base

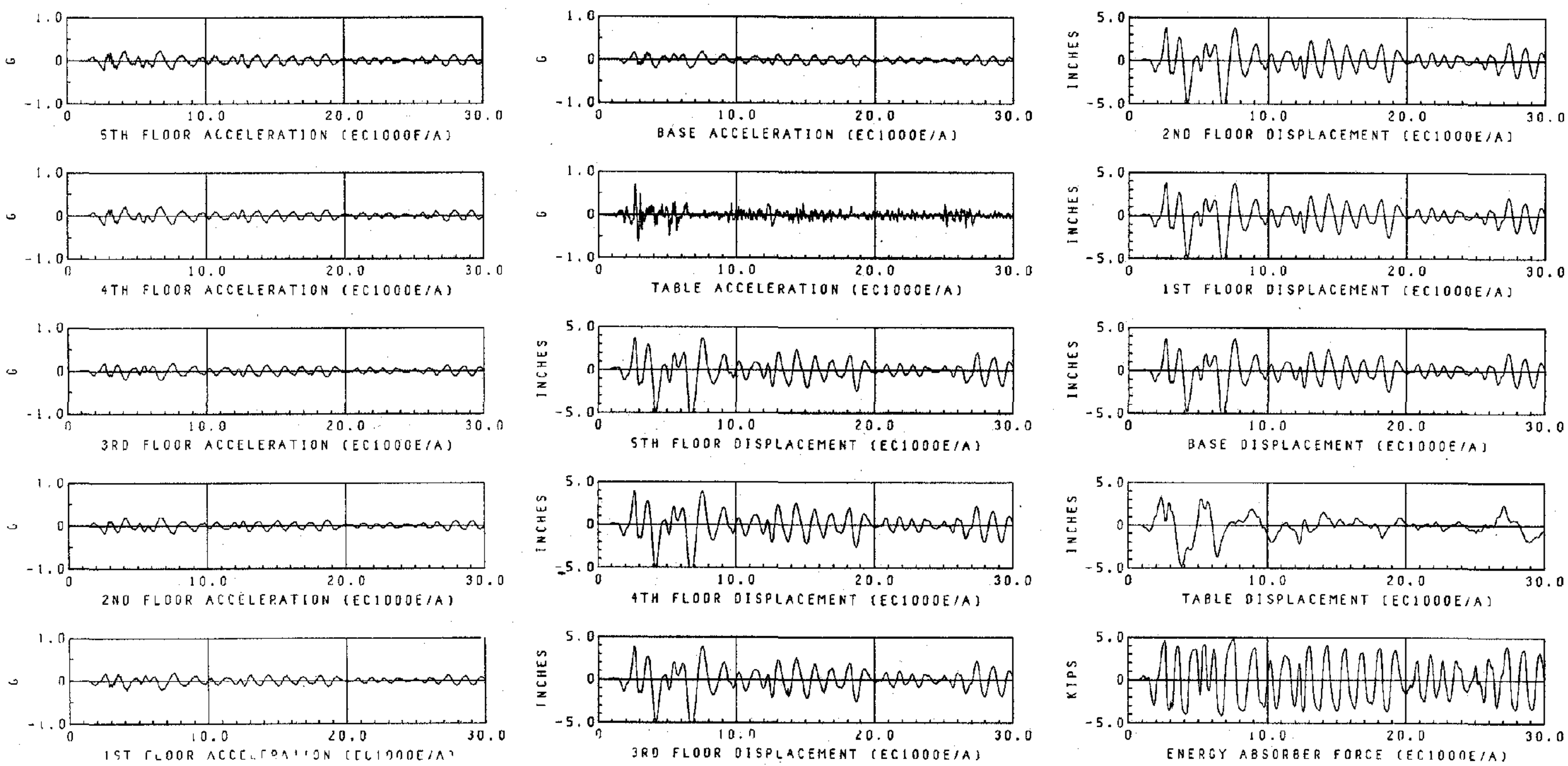

Figure 19(e) Acceleration and Displacement Time Histories and Energy Absorber Force: El Centro 1000 Ground Motion, Energy Absorber Base

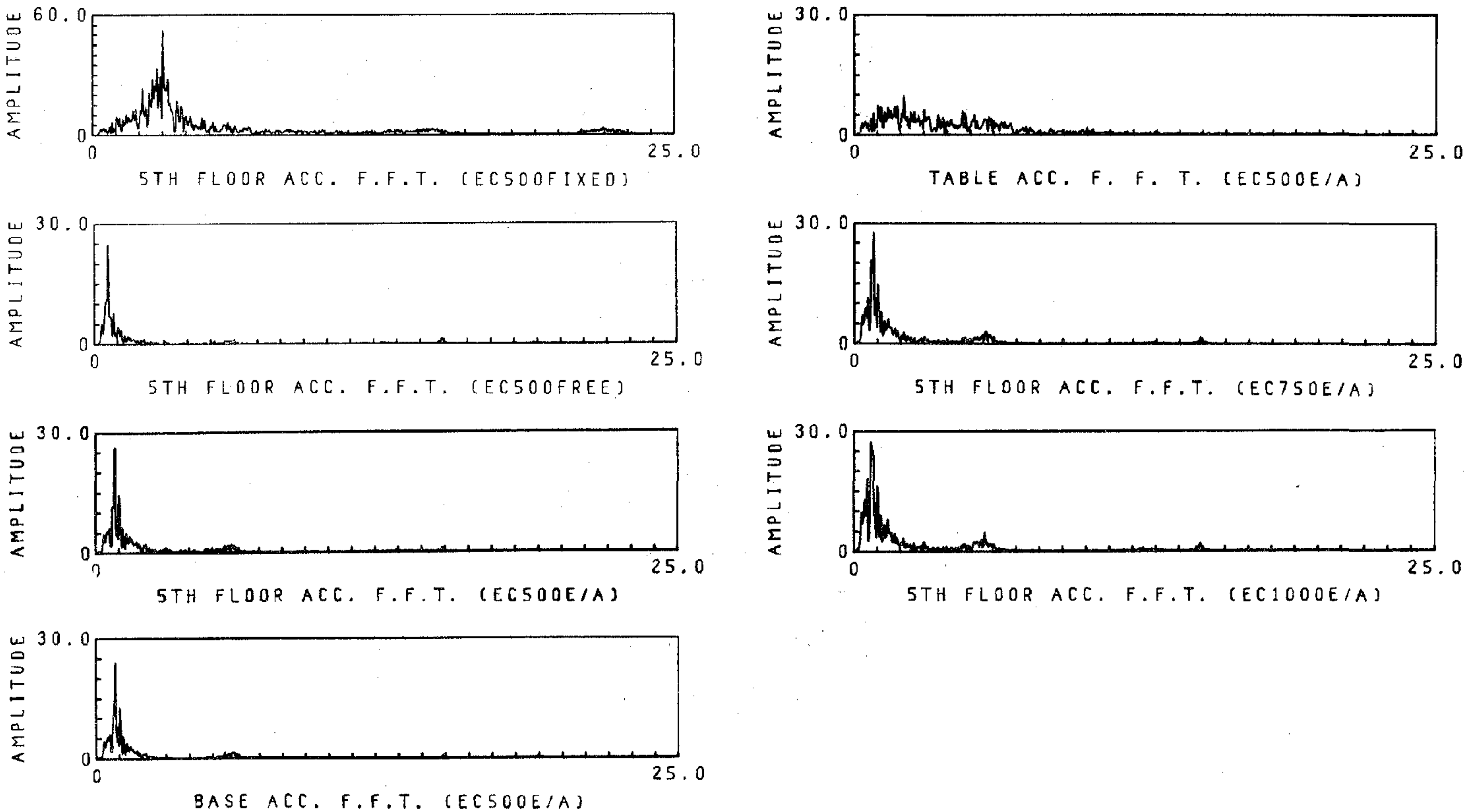

Figure 20 Fourier Transforms of Acceleration for El Centro Ground Motion

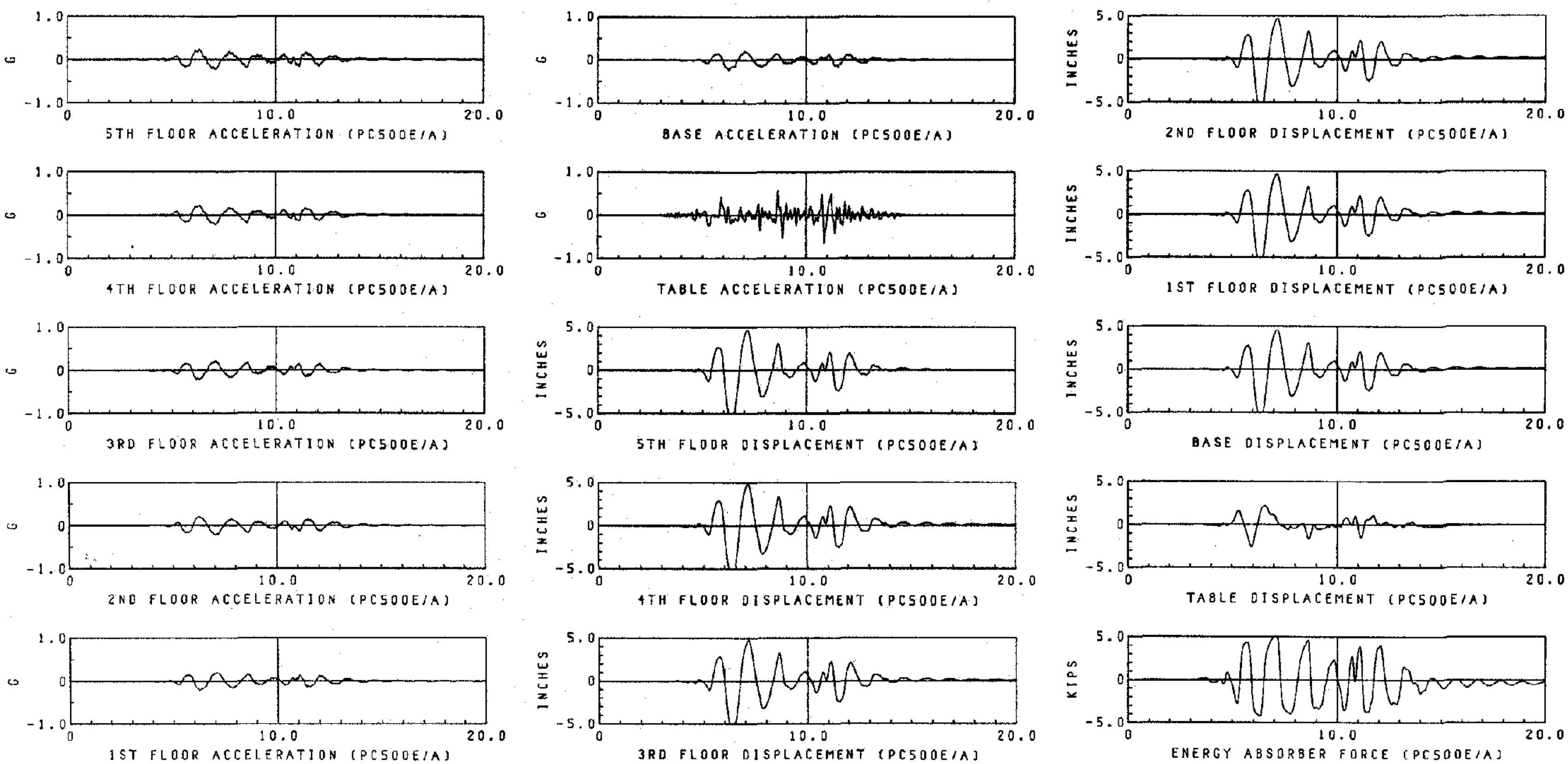

Figure 21 Acceleration and Displacement Time Histories and Energy Absorber Force: Pacoima Dam 500 Ground Motion, Energy Absorber Base

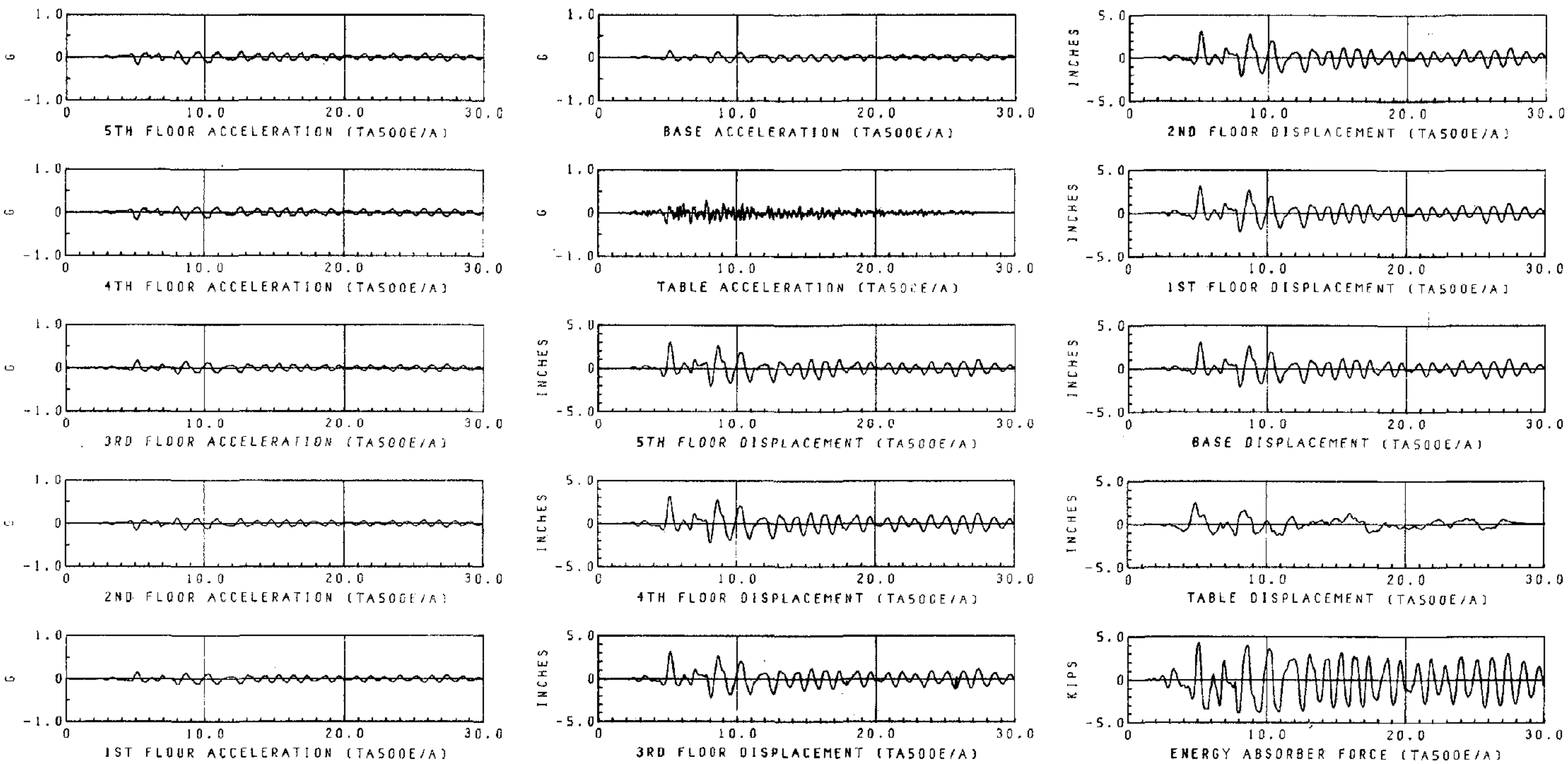

Figure 22 Acceleration and Displacement Time Histories and Energy Absorber Force: Taft 500 Ground Motion, Energy Absorber Base

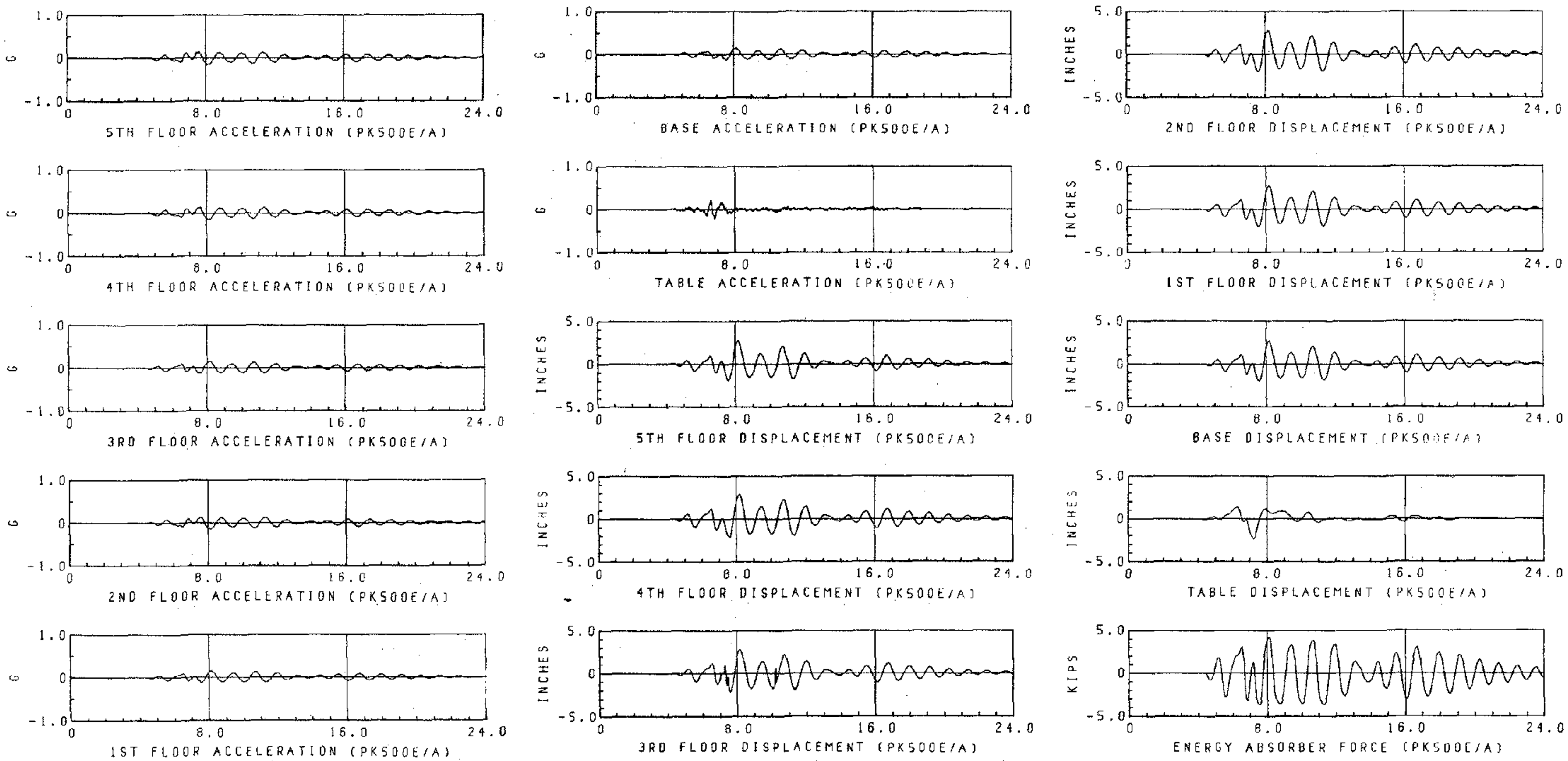

Figure 23 Acceleration and Displacement Time Histories and Energy Absorber Force: Parkfield 500 Ground Motion, Energy Absorber Base

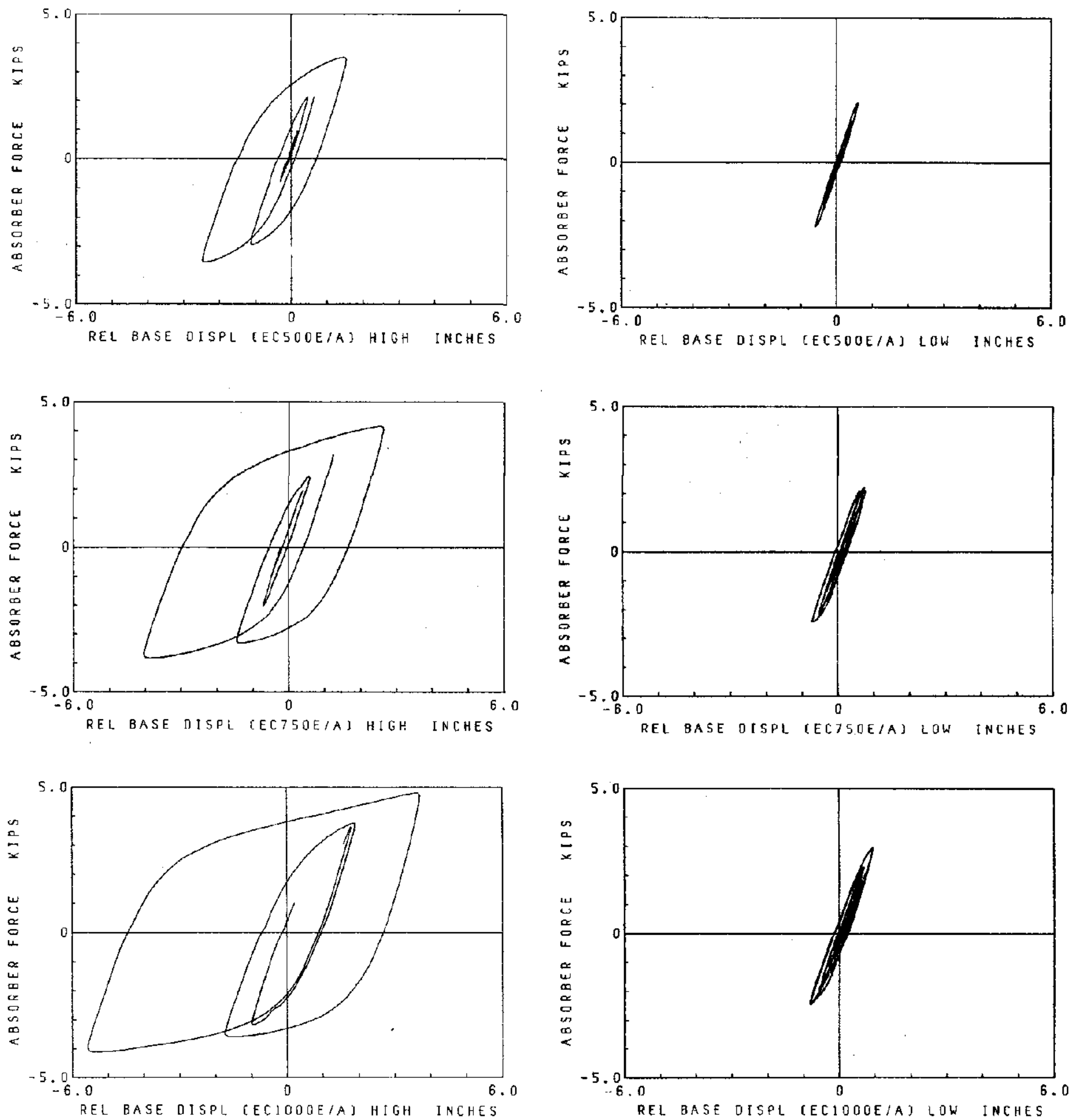

Figure 24 Force Displacement Curves for Cantilever Device for Four-Second Intervals of El Centro Ground Motion

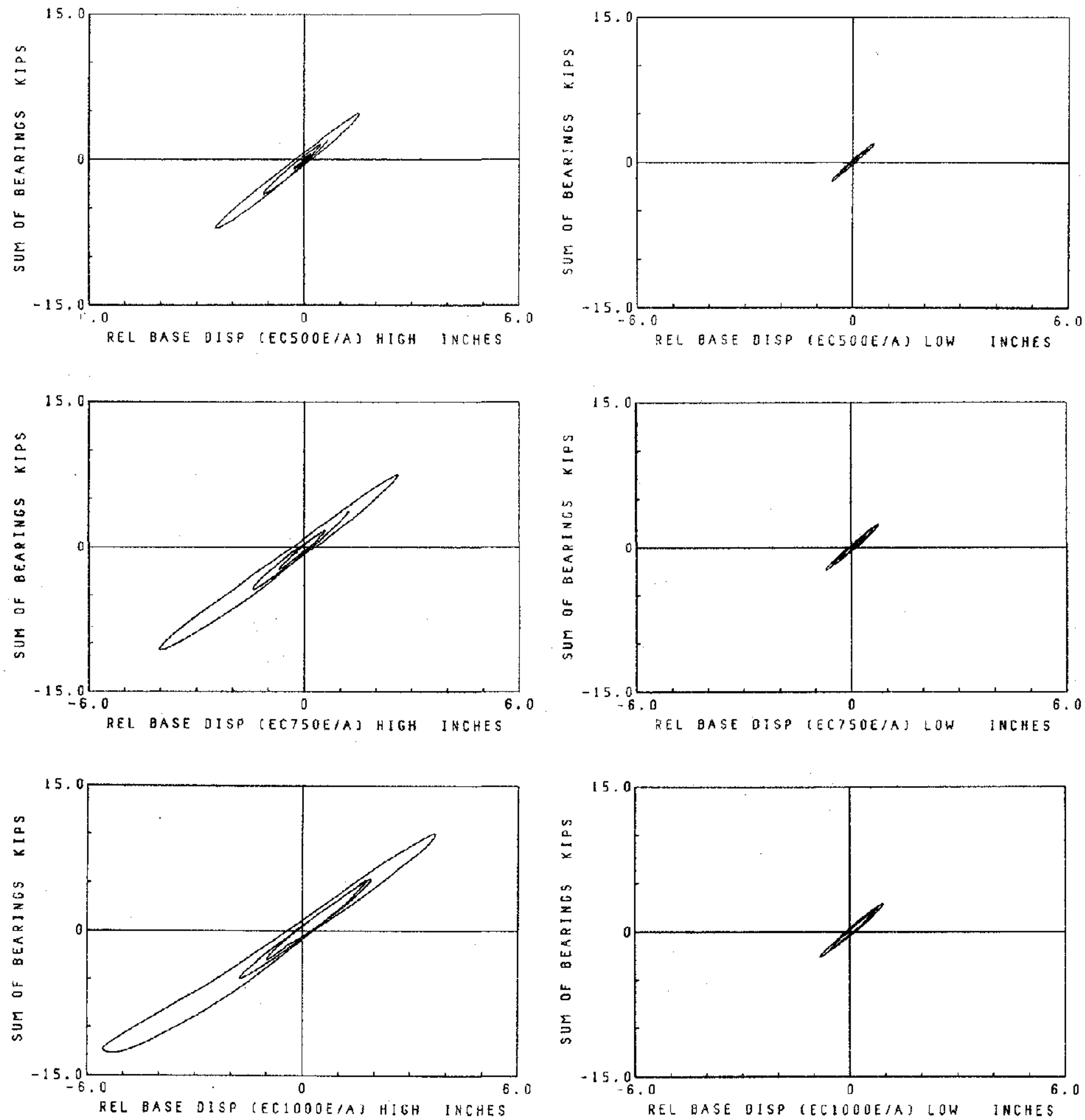

Figure 25 Force Displacement Curves for Bearings for Four-Second Intervals of El Centro Ground Motion

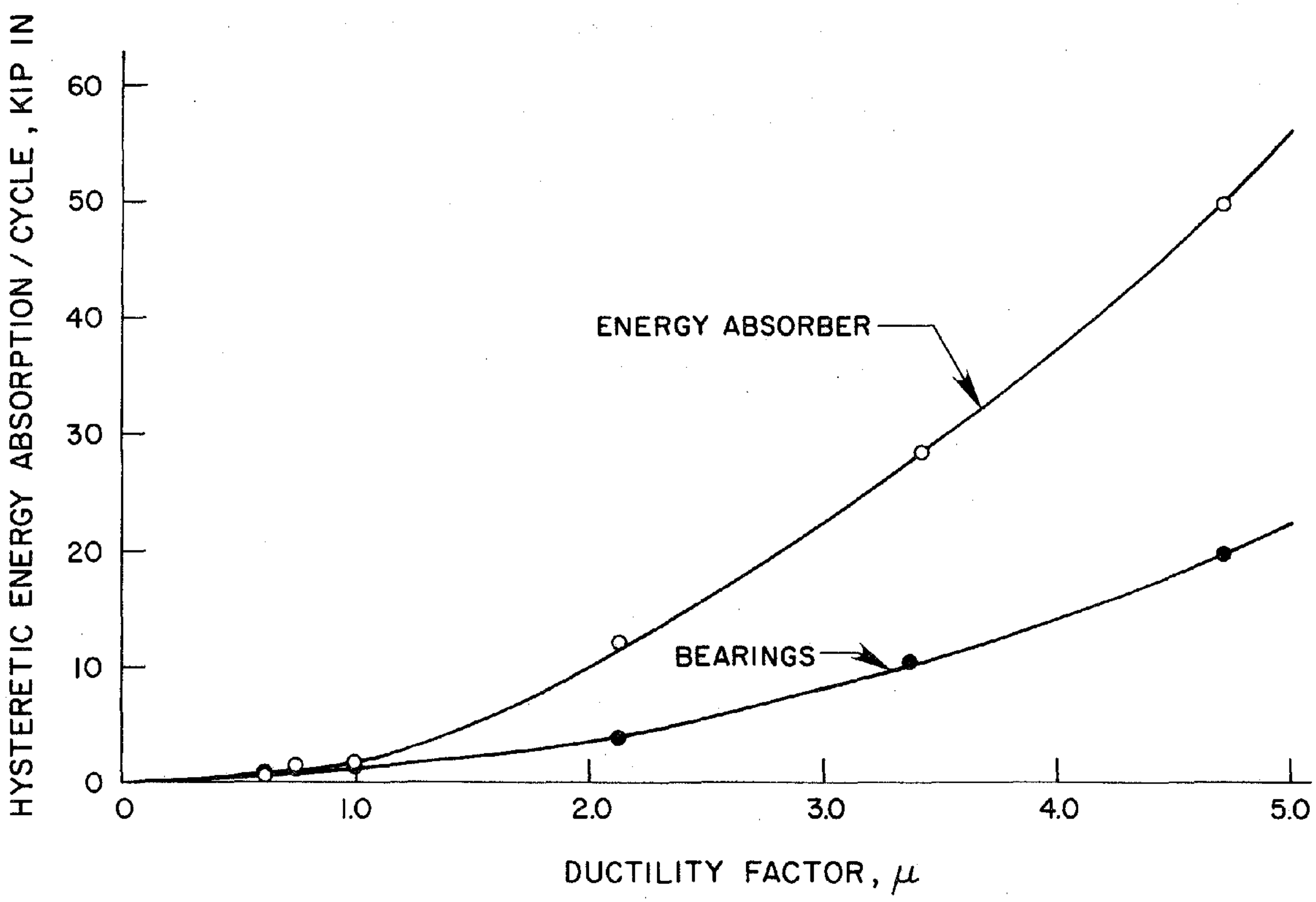

Figure 26 Energy Absorption versus Ductility for Bearings and Cantilever Device

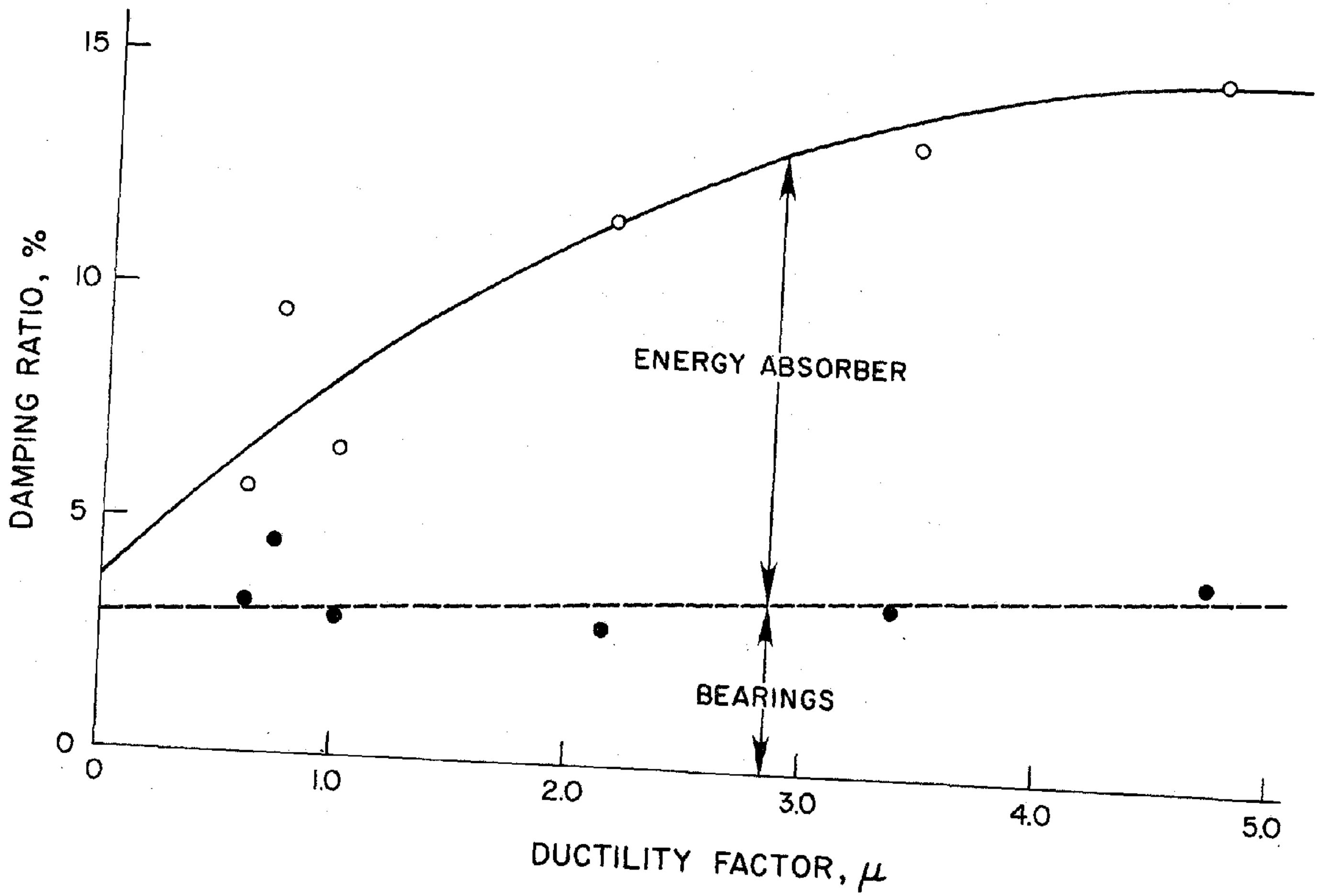

Figure 27 Equivalent Damping Ratio versus Ductility: Relative Contribution of Bearings and Cantilever Device

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