EPRI-NP--2918

DE83 902344

The Use of Base Isolation and Energy-Absorbing Restrainers for the Seismic Protection of a Large Power-Plant Component

NP-2918
Research Project 810-8

Final Report, March 1983

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EPRI PERSPECTIVE

PROJECT DESCRIPTION

The seismic base isolation concept has been employed in various types of structures and systems to mitigate severe earthquake-induced responses. Based on an earlier EPRI study, *A Review of Seismic Isolation for Nuclear Structures* (EPRI Special Report NP-1220-SR), it was concluded that potential benefits of employing seismic isolation in nuclear power plants are very significant, and further studies in this regard are warranted. Therefore, under its Soil-Structure Interaction Project (RP810), EPRI sponsored experimental studies of selected seismic isolation systems both in the field and on the shake table.

This report for RP810-8, *The Use of Base Isolation and Energy-Absorbing Restrainers for the Seismic Protection of a Large Power Plant Component,* is one of the three final reports resulting from these studies. The other two reports are:

- EPRI NP-2917, *Testing of a Natural Rubber Base Isolation System by an Explosively Simulated Earthquake*
- EPRI NP-2919, *The Influence of Base Isolation on the Seismic Response of Light Secondary Equipment*

PROJECT OBJECTIVES

Under seismically induced loads, the dynamic coupling between a large component of a nuclear power plant, such as a reactor vessel or steam generator, and its connecting structures introduces uncertainties in specifying seismic input to the components. One objective of this study was to assess experimentally the significance of the dynamic coupling, and the other objective, which was more important, was to investigate the effectiveness of using a base isolation device and energy-absorbing restrainers in minimizing this coupling effect. A model consisting of a scaled steam generator attached to a frame structure on a shake table was seismically tested to achieve the above objectives.

PROJECT RESULTS

Eighty-eight seismic shake table tests were conducted on four different test configurations:

- Configuration A: Fixed-base steam generator uncoupled from the frame structure
- Configuration B: Fixed-base steam generator laterally connected to the frame structure
- Configuration C: Base-isolated steam generator uncoupled from the frame structure
- Configuration D: Base-isolated steam generator coupled with the frame structure by energy-absorbing restrainers

Comparison of test results between configurations A and B shows that the coupling of the steam generator and frame structure in general reduced the seismic responses of the steam generator significantly but increased only slightly the responses of the frame structure. Depending on the seismic environment tested, a 50% reduction of acceleration response was measured at the top of the coupled steam generator model. The results demonstrate the significance of dynamic coupling.

Comparison of results between configurations A and C shows that the use of a base isolation device effectively reduced the steam generator seismic responses. The reduction factor was as high as 15 on some measured accelerations. However, to effectively control the excessive relative displacements induced by the base isolation, energy-absorbing ductile restrainers were recommended. Study of the results between configurations C and D indicates that among various restrainers tested, the 1/4-in.-thick device yields the most desirable response. The actual application of such a combined base isolation and energy-absorbing restrainer system to an actual large power plant component has not yet been investigated.

Y. K. Tang, Project Manager
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ABSTRACT

Analysis of the seismic response of large components in power plants is complicated by interaction between the component and the structure. In large components such as the steam generator this interaction cannot be neglected in forming accurate estimates of the response. Further, the presence of cracks in the internal piping of some steam generators has led to their integrity under seismic action being questioned. The experimental program described herein was initiated by the Electric Power Research Institute of Palo Alto, California, to provide an experimental assessment of the influence of interaction on the seismic response of such a large compoment.

An additional part of the experimental program was to investigate the feasibility of using rubber bearing isolation as a retrofit strategy to improve the structural integrity of the component against seismic loading.

A further aspect of the experimental study was to investigate the use of energy-dissipating restrainers in connecting the component to the primary structure. The experimental test program investigated the response of a steam generator model mounted on natural rubber isolation bearings and connected to the primary structure by a system of energy-absorbing restrainers the purpose of which is to control the response of the isolated system by absorbing the kinetic energy generated by seismic ground motion.

The report describes the design and construction of the steam generator model and model of the primary structure in which it is mounted and the results of an extensive series of simulated ground motion tests carried out on the shaking table at the Earthquake Engineering Research Center of the University of California at Berkeley. In these tests the steam generator model was supported in a conventional manner and on a natural rubber isolation bearing. The interconnection of the model and structure involved the use of a variety of restrainers.

ACKNOWLEDGMENTS

The research described in this report was sponsored by the Electric Power Research Institute under agreement number RP810-8. The author is grateful to Dr. H. T. Tang and Dr. Y. K. Tang of the E.P.R.I. for their encouragement and support during the testing program.

The rubber bearings used in the experiments were designed by C. J. Derham and A. G. Thomas of the Malaysian Rubber Producers' Research Association of the United Kingdom and were manufactured by the Andre Rubber Company of Subiton, England. Their contribution to the project is gratefully acknowledged.

CONTENTS

TABLES

ILLUSTRATIONS

SUMMARY

Seismic analysis continues to be a large portion of the design effort for power plants and as seismic requirements for both existing and new plants are increased there is a need to ensure that design techniques do not lead to excessively conservative designs. For this reason the Electric Power Research Institute initiated a program of experimental research on the seismic behavior of a large power plant component. The steam generator was selected to represent the large component to be investigated in this research program. Corrosion cracking has been found in steam generator tubing in some operating power plants and the performance of such cracked tubes under seismic loading needs examination. To deal with this problem, a more accurate specification of the seismic input to the component itself is required; and it was hoped that this experimental program would provide a data base for the generation of suitable input motions. The experiments could be used to check on computer programs used to generate the input, assess the influence of interaction between the component and the primary structure, and also suggest possible simplifications in the analysis of the response from which an estimate of the seismic hazard to the cracked tubes could be made. The tests cannot directly provide data on the seismic hazard to the steam generator tubes, but the results could be used to verify the accuracy of a computer simulation intended for this purpose.

The second part of the experimental study reported here is an investigation of the feasibility of using base isolation as a retrofit strategy for large components, such as the steam generator, if it were decided that such a component in an existing plant was subject to seismic hazard either because of some weakening of the system caused by the operation of the plant, or alternatively because of a change in the regulatory environment requiring increased seismic resistance. Seismic isolation is a well-known earthquake-resistant design approach which is being used in France for the seismic protection of entire power plants. In this strategy, the entire power plant is built on an isolation platform carried on a system of multi-layer elastomeric bearings. The purpose of the isolation system is to control the seismic loading transmitted to the structure on the isolation platform and, in turn, to reduce the motion transmitted to equipment and piping. The concept has been used for entire buildings as well as power plants, and it is an obvious suggestion that it might be used for large components in existing plants. Thus, as part of the experimental program, in order to study the influence of such a system on the response of large components, tests were carried out with the steam generator mounted on an isolation system. Since the seismic input to the component is transmitted through the primary structure which is itself not isolated, it is clear that such partial isolation cannot be as effective as total isolation of the entire plant. It will be shown, however, that the results indicate significant reductions in the seismic loading applied to the generator at the expense of increased relative displacements between component and structure.

A third part of the testing program was to study the use of yielding or energy-absorbing restrainers in the connection between the steam generator and the primary structure. Such energy-absorbing restrainers, developed in previous research on the use of energy-absorbing devices in other structural systems has been suggested for piping in power plants and some experimental work on their use, as an alternative to snubbers, for piping has been carried out. Determination of their potential for use with large components was part of the present study.

The test results indicate that the use of base isolation in a large component can be beneficial in reducing the accelerations experienced by the component and the primary structure. The results also indicate that there is a significant advantage in using energy-absorbing restrainers when the component is isolated. The large relative displacements that occur when the component is isolated can be effectively used to dissipate large amounts of seismically induced energy in the composite system leading to reduced response in both component and primary structure.

Even in the case of a large component in a conventional system, the use of yielding restrainers can be beneficial in reducing seismic response. Although the relative displacements are not as great, the energy dissipation can have a significant effect on the response of the system.

The experimental research reported here indicates that base isolation and energy-absorbing restrainers might be a viable retrofit strategy for existing systems with large components having potential seismic hazard.

1. INTRODUCTION

The seismic analysis of equipment in complex structures such as power plants remains one of the most difficult problems of structural analysis. For light items of equipment in circumstances where the interaction between the equipment and the structure can be neglected, the main difficulties arise in the definition of the input motion. Whereas for large components where interaction between the equipment and the primary structure cannot be neglected, the analysis of the combined system can be very costly in addition to the problems of defining the input. Seismic analysis continues to be a large portion of the design effort for power plants and as the regulatory agencies increase the seismic requirements for both existing and new power plants, there is an increasing need to ensure that the design techniques do not lead to excessively conservative designs. For this reason, and also with a view to providing both data for the verification of existing seismic analysis programs and insight into the interaction during seismic loading of a large component and the primary structure in which it is housed, the Electric Power Research Institute (EPRI) instigated a program of experimental research on the seismic behavior of a large component in a power plant. A description of the program is given in this report.

The steam generator was selected to represent the large component to be investigated in this research program. Corrosion cracking has been found in steam generator tubing in some operating power plants and the performance of such cracked tubes under seismic loading needs examination. To deal with this problem, a more accurate specification of the seismic input to the component itself is required; and it was hoped that this experimental program would provide a data base for the generation of suitable input motions. The experiments could be used to check on computer programs used to generate the input, assess the influence of interaction between the component and the primary structure, and also suggest possible simplifications in the analysis of the response from which an estimate of the seismic hazard to the cracked tubes could be made. The tests cannot directly provide data on the seismic hazard to the steam generator tubes, but the results could be used to verify the accuracy of a computer simulation intended for this purpose.

The second part of the experimental study reported here is an investigation of the feasibility of using base isolation as a retrofit strategy for large components, such as the steam generator, if it were decided that such a component in an existing plant was subject to seismic hazard either because of some weakening of the system caused by the operation of the plant, or alternatively because of a change in the regulatory environment requiring increased seismic resistance. Seismic isolation is a well-known earthquake-resistant design approach which is being used in France for the seismic protection of entire power plants [1]. In this strategy, the entire power plant is built on an isolation platform carried on a system of multi-layer elastomeric bearings. The purpose of the isolation system is to control the seismic loading transmitted to the structure on the isolation platform and, in turn, to reduce the motion transmitted to equipment and piping. The concept has been used for entire buildings [2,3] as well as power plants, and it is an obvious suggestion that it might be used for large components in existing plants. Thus, as part of the experimental program, in order to study the influence of such a system on the response of large components, tests were carried out with the steam generator mounted on an isolation system. Since the seismic input to the component is transmitted through the primary structure which is itself not isolated, it is clear that such partial isolation cannot be as effective as total isolation of the entire plant. It will be shown, however, that the results indicate significant reductions in the seismic loading applied to the generator at the expense of increased relative displacements between component and structure.

A third part of the testing program was to study the use of yielding or energy-absorbing restrainers in the connection between the steam generator and the primary structure. Such energy-absorbing restrainers, developed in previous research on the use of energy-absorbing devices in other structural systems [4,5] has been suggested for piping in power plants [6] and some experimental work on their use, as an alternative to snubbers, for piping [7] has been carried out. Determination of their potential for use with large components was part of the present study.

The construction of a model of the steam generator and its incorporation into a model of the primary structure (and the mounting of the entire system on the 20 ft by 20 ft (6 m by 6 m) shaking table at the Earthquake Simulator Laboratory of the Earthquake Engineering Research Center of the University of California) was a rather costly and time-consuming task, so it was important to use the system fully. Therefore, the three separate aspects of the test program outlined above were implemented. The models were roughly one-third geometrically scaled and the input earthquake loading comprised a large number of standard earthquake records time scaled by a factor of $\sqrt{3}$. Under this scaling the stresses and accelerations experienced by the model will be the same as in the prototype and the displacements will be reduced by the scale factor. Scaling is not particularly important in this experiment in that the model frame in which the steam generator is located is not an accurate simulacrum of a nuclear structure.

This report describes the design of the various models used in the study, describes their connections by conventional elements and by yielding elements, and gives results for the seismic interaction between the large component and the primary structure. It also presents data on the influence of the energy-absorbing action of the yielding restrainers on the response of the steam generator both for conventional fixity and in the isolated configuration. The results are used to suggest optimal combinations of isolation and energy absorption.

2. EXPERIMENTAL MODELS AND TEST FACILITIES

a) Model of Primary Structure

The experimental model for the primary structure, detailed in Figure 1 and shown mounted on the table in Figure 2, is a five-story, three-bay welded steel frame. The main members of the frame are W 4 x 13 beams and W 6 x 8.5 columns in A36 steel. The story height is 3 ft (0.91 m) for the upper stories and 4.5 ft (1.37 m) for the lowest story. The external bays are 6 ft 6 in. (1.98 m) and the internal bay is 5 ft (1.52 m). The overall length of the frame at the column feet is limited by the table size to 20 ft (6 m). The height of the frame is roughly 18 ft (5.49 m) from the table to the top of the concrete blocks and the depth in the unloaded direction is 6 ft (1.83 m). Each floor of the frame carries two 4,000 lb (1,815 kg) and two 2,000 lb (907 kg) concrete blocks to increase the inertial loading.

Because the lowest story of the frame is relatively flexible compared to the upper stories, an unrealistic flexible first-story action would occur. Thus, K-bracing in the form of two sets of 2 in. x 2 in. x 1/4 in. (51 x 51 x 6.3 mm) double angle bracing was incorporated in the lowest central bay.

The columns are connected through base plates to a pair of W 8 x 31 beams which are anchored to the shaking table by stressed rods. The frame carries a dead load of 60,000 lb (27,200 kg) and by itself weighs approximately 4,500 lb (2,020 kg).

b) Model of Steam Generator

The design of the model for the steam generator was subjected to certain constraints imposed by the frame model. To fit in the central bay, it could not exceed 4.5 ft (1.37 m) in diameter and would, in fact, have to be less than this to allow for placement of the yielding restrainers. To control costs it had been decided that surplus pipe from gas pipeline construction (API schedule 40) would be used to build the model and this limited the choice of the two diameters of the model. A prototype steam generator design was used as a guide, and the design of the model was selected to correspond as closely as possible to the prototype proportions, within these constraints. The model dimensions are shown in Figure 3. The model is made of a 60 in. (1.52 m) length of 42 in. (1.07 m) pipe and a 103 in. (2.62 m) length of 36 in. (0.91 m) pipe joined by a conical reducer connection rolled from 3/8 in. (9.53 m) plate; each end is capped by a standard dished end also rolled from 3/8 in. (9.53 mm) plate. The thickness of all pipe sections was 3/8 in. (9.53 mm). The model was constructed from these pieces using full penetration welds. The joints were prepared by oxy-acetylene cutting and disc grinding. In order to ensure alignment of the various parts the metal arc welding was carried out in a specially developed rotating jig.

The design of the support fixture corresponds to that of the prototype as far as is possible within the constraints imposed by the requirement that it be readily modified to include the isolation system. Four 2 in. (50.8 mm) diameters pipes were welded to the lower dished cap of the model and these were, in turn, welded to a 4 ft by 4 ft, 1 inch thick (1.22 m by 1.22 m, 25.4 mm) plate. Thus, the plate could be bolted to the frame model while resting on the isolation bearing. The support provided lateral rigidity but was sufficiently flexible in bending to act as a soft moment spring. When the bolts attaching the plate to the frame were removed, the entire weight of the generator was carried by the isolation bearing. This condition produced very low lateral stiffness with effectively zero moment stiffness. These support conditions are not intended to be a precise match to actual conditions in a steam generator but are as close as could be achieved within the limitations of the shaking table set-up.

The inertia of the model was increased by filling it with water. The entire weight of the generator when completely filled with water was 11,430 lb (5,185 kg).

The location of the center of gravity is shown in Figure 3 at 105 in. (2.67 m) above the base plate and the estimated moment of inertia about an axis perpendicular to the plane of the diagram through the center of gravity is 42.65×10^6 lb $in.^2$ (124,500 kg m^2).

c) Natural Rubber Isolation Bearing

A single bearing was used to provide isolation for the steam generator. The bearing was one of a set of isolation bearings previously used to isolate the entire structural model. These bearings were used with this frame model in a study of the influence of base isolation on the seismic response of light equipment. The bearings, manufactured by the Andre Rubber Company Ltd., are of natural rubber reinforced by steel plates. The complete bearing comprises ten modules each containing two 1/4 in. (6.35 mm) sheets of natural rubber and three 1/8 in. (31.8 mm) steel plates, the ten modules being epoxied together. The epoxy does not transmit shear force between modules, steel discs 1/4 in. (6.35 mm) thick are keyed into the 1/8 in. (3.178 mm) thick top plate of one module and into the 1/8 in. (3.178 mm) thick bottom plate of the module below. Similarly, 1/4 in. (6.35 mm) thick disks welded to the generator support plate and to a base plate on the frame transmit shear forces between the structure and the bearing, and between the bearing and the steam generator. This arrangement reduces the possibility of tension stress being induced in the rubber layers. The horizontal stiffness of a multi-layer bearing depends on both the shear modulus and the vertical load carried by the bearing. As part of the earlier study [8] involving full structural isolation, the bearings were statically tested in a specially design press in which two bearings were loaded with a specified vertical load and then horizontally loaded at midheight. The horizontal loading curves for various vertical loads, P_v, are shown in Figure 4. At a vertical load of 10,000 lb, the horizontal stiffness of the bearing was estimated to be 720 lb/in. (12.86 kg/mm). The bearing as it was installed is shown in Figure 5.

A tall structure such as the steam generator is, of course, not stable when supported only at the base by a system with zero moment stiffness. In order to allow the generator model to be tested in the absence of restrainers it was essential to stabilize it. This was done by connecting the steam generator to the top of the frame by four coil springs arranged diagonally as shown in Figure 1. The springs were prestressed to maintain tension during all excursions. The stiffness of this connection was measured in situ to be 26.67 lb/in. (0.476 kg/mm). This measurement was obtained by applying a known horizontal load to the top of the steam generator and measuring the resulting relative displacement between the generator and the frame.

These springs are only necessary when the steam generator is in the isolated condition and with no lateral supports. When the steam generator is fixed at the base or when lateral constraint is provided by the yielding restrainers, the effect of these top springs on the dynamic response is completely negligible.

d) Energy-Absorbing Restrainers

The energy-absorbing devices used in this test series are tapered, cantilever beams of hot-rolled, low carbon mild steel, similar to, but much smaller than, the devices used as energy absorbers in the study of light-equipment response when the entire structure was isolated [8]. The energy-absorbing mechanism is large elastic-plastic deformation. 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 [8] it was shown that this is a necessary condition if continuing plastic action of the device is to be ensured.

At the maximum displacement to which the devices were subjected in the present test series, plastic strain was estimated to be 1.8 percent, 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. Therefore the behavior of the system with such devices is similar to that of a conventional structure for minor excitations. In general the structure will then amplify the ground acceleration. The devices yield under more intense excitation and produce large hysteresis loops as the structure vibrates. The tangent stiffness of the steel when yielding is between 5 and 10 percent of the elastic stiffness. Thus, the frequencies of the structure are lowered and an effective damping is introduced and the degree of damping produced thus depends on ground motion intensity.

On the basis of the successful use of the tapered type of restrainer used in the base isolation study [8], a set of tapered restrainers was designed and manufactured for the steam generator experiments. The dimensions of the devices were selected with the constraint of a maximum displacement of $\pm 2\frac{1}{2}$ in. (63.5 mm) imposed by the clearance between the generator and the frame. It was necessary to provide a design that would allow a large variation in yield level for the restrainers because of the very different characteristics of the responses in the conventionally based and isolated conditions. Thus, the base width and taper were fixed and the variable parameter was the device thickness. The thicknesses used were 1/8 in. (3.175 mm), 1/4 in. (6.35 mm), 1/2 in. (12.7 mm), and 1 in. (25.4 mm) in all the dimensions shown in Figure 7. In all, five yielding restrainers were used: 1/8 in., 2 x 1/8 in. (two 1/8 in. energy-absorbing devices clamped together), 1/4 in., 1/2 in., and 1 in. The 1 in. (25.4 mm) device was found to be sufficiently rigid to perform elastically, and it was used to model a conventional connection between the steam generator and the primary structure. The 1/8 in. (3.175 mm) thick and 1/4 in. (6.35 mm) thick restrainers were manufactured from 1020 mild steel and the 1/2 in. (12.7 mm) and 1 in. (25.4 mm) thick restrainers from A36 mild steel. The yield characteristics of these two steels do not differ significantly.

The energy-absorbing restrainers were attached to the frame vertically. The tapered end was attached to a pin on roller bearings which in turn were attached to a connection rod. The rod carried a load cell instrumented with a strain gage, and this in turn was connected to collars on the steam generator model. Two energy-absorbing restrainers, symmetrically placed, were attached to each of the two collars on the generators at levels which correspond roughly to the upper lateral supports in the prototype. The forces in each energy absorber were measured continuously during each test. The forces recorded on the two devices at each level did not differ by more than a few percent. Hence, the response was symmetric. The details of the connections are given in Figure 8 and photographs of the energy-absorbing restrainers as installed are shown in Figures 9 and 10.

e) Earthquake Simulator

The experiments reported here were carried out at the Earthquake Simulator Laboratory at the Earthquake Engineering Research Center at the Richmond Field Station of the University of California, Berkeley. The main dynamic test facility is a 20 ft x 20 ft (6 m x 6 m) shaking table with associated control equipment as described by Rea and Penzien in reference 9.

The shaking table is a 20 ft x 20 ft x 1 ft (6 m x 6 m x 0.305 m) prestressed concrete slab, driven independently in the vertical direction and in one horizontal direction by servo-controlled actuators. The 100,000 lb (453 600 kg) dead weight of the table plus the weight of a model is supported by differential air pressure during operation. The vertical actuators are thus relieved of any static load-carrying function.

The control signals for the two degrees of freedom are in the form of analogue displacement time histories on magnetic tape, obtained normally through a double integration of acceleration time histories. The table motion has been demonstrated to have good repeatability.

The limits of the table motion for the table alone are given in reference 9. The displacement limits result from the actuator strokes; oil-pumping capacity limits the velocity, and the acceleration is limited by actuator force capacities and the oil column resonance of the drive system. With a model on the table, the acceleration limits are somewhat lower; the other limits are not appreciably affected.

The data acquisition system, centered on a NOVA 1200 minicomputer equipped with a Diablo 31 magnetic disk unit, is capable of discretely sampling up to 128 channels at rates of up to 100 samples/sec/channel. Transducer signals, in analogue form, 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 nine-track magnetic tape drive for permanent storage.

f) Instrumentation

In the experimental program seven channels were devoted to monitoring the shaking table function. The table parameters of primary importance were the horizontal and vertical input accelerations. The response quantities of interest were horizontal accelerations in the primary structure model at each floor level, the horizontal accelerations in the generator model at these levels, the corresponding absolute displacements and the relative displacements between generator and frame. The relative displacement and forces at the restrainers are also important and the relative displacement at the base in the isolated condition.

A total of 32 channels of dynamic response data were used for the combined model, namely: 11 horizontal accelerations, 1 vertical acceleration, 5 absolute frame displacements, 11 relative displacements, and 4 restrainer forces. The accelerations were measured by Kistler, Setra, and Statham accelerometers, the absolute displacements by Houston Scientific linear potentiometers with a range of ±7.5 in. (±190.5 mm) and relative displacements at the energy-absorbing restrainer levels were measured using direct current displacement transducers with a range of ±3 in. (±76.2 mm).

Two sets of load cells were designed and built for this project. They were thin-walled $1\frac{3}{16}$ in. (30.16 mm) diameter tubes of aluminum carrying strain gages. Two sets were necessary because of the large range of forces generated by the restrainers. One set had an upper load limit of 500 lb (2.22 kN) and was used for the 1/8 in. (3.178 mm), 2 x 1/8 in. (2 x 3.178 mm), and 1/4 in. (6.35 mm) restrainers; the other set had an upper load limit of 5,000 lb (22.24 kN) and was used for the 1/2 in. (12.7 mm) and 1 in. (25.4 mm) restrainers.

g) Static Testing of Tapered Cantilever Energy-Absorbing Restrainers

The energy-absorbing restrainers were machined from 1020 and A36 mild steel to the dimensions shown in Figure 7. Several of the specimens were subjected to displacement-controlled, pseudo-static loading to verify that the device could produce the energy absorption needed in the tests and that the device would survive several cycles of testing.

The devices were tested on an MTS Hydraulic Service Manifold Series 283 testing machine coupled with an MTS Servogram Model 204-31, 50,000 lb (22,680 kg) capacity hydraulic ram and loading rig; input to the system was displacement controlled. All devices were subjected to cyclic sinusoidal 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 ±10 V 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. A schematic of the experimental arrangement is given in Figure 11 and a photograph in Figure 12. Figure 13 is a photograph of the energy-absorbing restrainer device in the test rig.

The tapered cantilever energy-absorbing restainers were tested under sinusoidal loading of 0.1 Hz at displacements of ±1 in. (±25.4 mm) and $\pm 1\frac{1}{2}$ in. (±38.1 mm). The displacement required to induce initial yielding of the specimens varied with the thickness of the device.

On the basis of preliminary tests, the decision was made to use one 1/8 in. (3.178 mm) thick device, two 1/8 in. (3.178 mm) thick devices clamped together, one 1/4 in. (6.35 mm) thick device, and one 1/2 in. (12.7 mm) device as restrainers in the dynamic experiments. Static hysteresis loops for those restrainers were measured in the test rig and are shown in Figure 14. These will be compared with the dynamic hysteresis loops measured directly during seismic loading.

The tapered cantilever energy-absorbing devices have, in addition, been tested to failure for different peak displacements and under displacement-controlled sinusoidal and random loading. The lifetimes of these restrainers, in terms of cycles to which the restrainers would be subjected during an earthquake, is more than adequate and furthermore the devices are reliable, cheap, and easily fabricated and installed. Table 1 gives the static properties of each of the restrainers used in the dynamic testing of the steam generator.

The values of yield displacement and yield load given in Table 1 correspond to elastic-perfectly plastic behavior. It is a characteristic of these steels that such response occurs only on initial monotonic loading; after unloading and reloading, the yield displacement and yield load are no longer precisely defined, the load displacement curve for the device being smooth. The values in the table are for comparison purposes only.

3. DYNAMIC PROPERTIES OF STEAM GENERATOR-FRAME SYSTEM

a) Frame Frequencies and Mode Shapes

In the process of assembling the generator-frame model on the shaking table it was necessary to mount the unfilled generator model in the frame before loading the structure with concrete blocks. It was therefore not possible to study the dynamics of the frame without the generator. However, when the generator model rested on the isolation bearing with no restrainers connecting it to the frame, the response of the frame could reasonably be expected to be independent of the generator. In this condition, the system was subjected to several earthquake inputs. These are listed in Table 2. Fourier transforms of the recorded accelerations at each floor level were used to locate resonant frequencies. Typical cases are shown in Figure 15. The best estimate of the fundamental frequency of the frame that can be made from these data is 3.47 Hz. The higher modes do not show up very strongly in the fast Fourier transform plots. An estimate of the mode shape at 3.47 Hz can be made from the fast Fourier transform plot, and this is shown in Figure 16. The second mode has a frequency of approximately 11 Hz and the third a frequency of approximately 21 Hz. Estimates of the mode shapes corresponding to these frequencies can be made from the fast Fourier transform plots and these are shown in Figure 16.

b) Steam Generator Frequencies and Mode Shapes

Fixed-Base Case

The fixed-base dynamic properties of the generator model were determined by subjecting the system to a number of simulated earthquake inputs with the generator base plate bolted to the base of the frame, and no restrainers installed. Fast Fourier transforms of acceleration response records of the generator at the frame levels were determined. Typical plots are show in Figure 17. It is clear from these curves that the generator model was responding as a single-degree-of-freedom system with a natural frequency of 2.05 Hz. An estimate of the corresponding mode shape is shown in Figure 19 and, clearly, it results from the relative flexibility of the base plate. The generator model itself was sufficiently stiff that deformational modes could not be excited by the table.

Rubber Bearing Case

When mounted on the isolation bearing and tested with no restrainers, but with the top spring in place, the steam generator acted as a two-degree-of-freedom system with a very low fundamental frequency of 0.195 Hz and a mode shape that is almost entirely translational, actually corresponding to rotation about a point about two full lengths below the base. The second mode has a frequency of 2.00 Hz and a mode shape corresponding to rotation about a point 40 in. (101.6 mm) above the center of gravity. The Fourier plots are shown in Figure 18 and the corresponding mode shapes in Figure 19.

If the steam generator model is assumed to be a rigid bar with measured weight and center of gravity, supported on linear springs top and bottom the estimated frequencies (including the influence of inverted pendulum action) are 0.26 Hz and 1.51 Hz. The discrepancy between the measured and calculated values can be attributed to interaction between the frame and generator model at the top and between the generator and the table at the bottom.

c) Response of Combined Structure-Component System with Elastic Connections

The 1 in. (25.4 mm) thick restrainers acted as elastic connections between the structure and the generator, and when used in the fixed-base condition, the system most closely conformed to conventional connectivity.

The Fourier transforms of the acceleration response to several different inputs show that the composite system responds with two closely spaced modes with frequencies 2.75 Hz and 3.32 Hz. These are shown in typical fast Fourier transform plots for both the frame (Figure 20) and the steam generator (Figure 21). An estimate of the mode shapes of the combined system is shown in Figure 22 for the two frequencies.

A third mode appears in the frame accelerations at 11 Hz, but it is not very distinct in the steam generator response. It seems clear than the interaction between the generator and the frame modified the separate basic frequencies of 2.00 Hz and 3.47 Hz to produce the two modes at 2.75 Hz and 3.32 Hz. The third mode at 11 Hz is clearly the second mode of the frame alone and is relatively unaffected by the presence of the generator. A similar conclusion can be made for the third frame mode which becomes the fourth mode of the composite system However, even if the higher mode shapes and frequencies are not greatly changed by the presence of the generator, the response of the system is quite different. Figures 15 and 20 show the frequency content of the frame response at all five levels for the same earthquake input when the frame and the generator are uncoupled and when they are strongly coupled. The energy imparted to the frame in each of the two lowest modes in the strongly coupled condition is roughly one-third of that imparted to the lowest mode of the frame when they are uncoupled. The energy imparted to the generator appears to be responsible for this result. In fact, the accelerations in the generator in the coupled configuration are significantly higher than those in the frame for all four earthquake inputs as shown in Figure 23.

4. EARTHQUAKE SIMULATOR TESTS

a) Test Program

Four earthquake records were used in the test program: the El Centro N-S (1940), the Parkfield N65E (1966), the Taft S69E (1950), and the Pacoima Dam S16E (1971) records. These records were run on the table time scaled by a factor of $\sqrt{3}$ so that the data could be used to predict the response of a full-scale system. Table displacement and acceleration for each of these four records are shown in Figure 23. The peak acceleration that can be generated by the table during each individual run can be varied by adjusting the span number. A peak table dispacement of ± 5 in. (± 127 mm) corresponds to the span number 1000; lower span numbers correspond to proportionally lower displacements. Peak table accelerations for the same earthquake record are roughly proportional to the span number but the peak table acceleration at the same span number may vary slightly even for the same earthquake record for different model configurations because of structure-table interaction. Several different span numbers were used in preliminary testing to determine a suitable level for all tests.

The span numbers, earthquake records, and corresponding peak accelerations for the entire test program are given in Table 2. In this table, FB refers to the generator model in the fixed-base condition and RB to the isolated condition. Initially both horizontal and vertical input motions were used, but it was very clear from comparisons of the horizontal accelerations and displacements experienced by the models when tested with horizontal and vertical inputs and with horizontal input only that the vertical input had virtually no effect on the response of the system. Hence, in order to reduce the data acquisition requirements in the bulk of the testing program, only horizontal input was used.

In all, ninety different test runs were carried out and a great deal of dynamic test data was accumulated. The data were recorded in time history form on tape. The input motions vary from very small peak accelerations to a maximum input peak value of 0.8g.

b) Test Results

The data collected during the test are available as the time history of the output of each channel. As an example of this, the time histories of several output channels were plotted for the two extreme cases:

a) steam generator rigidly connected to the table and elastically connected to the frame by the 1 in. thick devices when subject to the El Centro input, shown in Figures 24(a) through (f);

b) steam generator on isolation bearings and not connected to the frame, also for the El Centro input, and shown in Figures 25(a) through (d).

From comparison of Figure 24(a) and Figure 25(a), it appears that the response of the frame is not considerably affected by the interaction with the steam generator. The peak acceleration in the frame is slightly reduced in the case of the composite system. This is thought to be due to the same observation that has been made for the Fourier transforms of these two cases. Less energy seems to be imparted to the frame when the generator is present in the fixed-base elastically restrained configuration than in the case when the frame response is independent of the generator.

The response of the steam generator is dramatically different for the two cases, (a) and (b). The typical characteristic of a base-isolated system can be observed in Figures 25(b), (c), and (d): greatly reduced accelerations and increased relative displacements. The peak acceleration is reduced approximately by a factor of 15 and the peak relative displacement is increased approximately by a factor of 1.8. The acceleration can also typically be seen to have a lower frequency in the base-isolated case than in the conventional case.

Finally, the forces at the connection points between the generator and the frame were plotted together (Figures 24(e) and (f)) with the corresponding displacements for the elastically connected system. The displacements—and hence the forces—at the top level are considerably higher than at the lower level due to the predominant rocking motion of the steam generator.

The extreme values of acceleration, displacement, and restrainer force measured during each run are given in Tables 3 through 11, and can be used to interpret trends in the response of the combined steam generator-frame system. For the frame responding on its own, the accelerations at the top vary from 1.08g for the Taft earthquake to 1.62g for the Parkfield earthquake. For the case when the frame is interacting with the generator, the accelerations at the top vary from 1.14g for the Taft earthquake to 1.34g for the Parkfield earthquake.

Interaction of Steam Generator and Frame

To assess the influence of interaction between the two components on the frame response, comparison should be made between the cases when the steam generator is rubber based with no restrainers connecting it to the frame, in which the frame is unaffected by the generator response, and the case when the generator is in the fixed-base condition and connected to the frame by the 1 in. (25.4 mm) restrainers which act as an elastic interconnection. To assess the influence of interaction on the generator response, we compare the generator response when it is fixed but not connected to the frame and when it is fixed and connected by 1 in. (25.4 mm) restrainers.

For the steam generator responding on its own, the accelerations at the top vary from 0.69g for the El Centro earthquake to 1.58g for the Taft motion. In the case, however, where the generator is interacting with the frame, the accelerations vary from 1.52g for the Parkfield earthquake to 2.26g for the Taft earthquake. This again demonstrates the significant effect that interaction of the two components has on the response of the steam generator. By contrast, it seems generally to be true that the frame is not significantly affected by the interaction of the two components.

Influence of Isolation on Steam Generator Response

The influence of the base isolation system in reducing the input to the steam generator depends on the choice of restrainer. For the fixed-base system, the results shown in Table 3 indicate that the steam generator has, for the El Centro record, accelerations varying linearly up to a peak of 1.66g, but when isolated, the accelerations are lower at the top (1.11g) but are more uniformly distributed along the component. Similar results (Tables 4 and 5) appear for the other earthquake inputs. These results are pictured in Figures 26(a) through 26(d) for the fixed-base condition and in Figures 27(a) through 27(d) for the rubber-base condition. It should be noted that the accelerations recorded in the frame structure are reduced when the steam generator is isolated. The reason that this is so is that when the generator is isolated but attached elastically to the frame, its predominant effect is to add mass to the frame and thus lower the basic frequency of the frame, moving it away from the frequency range of peak energy in the earthquake records. The isolation bearing also has significant damping and this will have the effect of reducing the entire system response. The maximum relative displacements between the frame and the generator at the top are 1.1 in. (27.94 mm) in the fixed-base condition and 1.8 in. (45.72 mm) when isolated. Thus, the considerable reduction is not obtained at the cost of large increases in relative displacement.

Influence of Energy-Absorbing Devices on Steam Generator Response

To assess the influence of the different energy-absorbing restrainers under the fixed-base conditions, reference should be made to Figures 28(a) through 28(c). It is clear that the accelerations in the steam generator decrease or, at least, do not increase as the energy-absorbing restrainer thickness increases from 0 to 1/4 in. (6.35 mm), but increase quite markedly beyond this. The results indicate that the 1/4 in. (6.35 mm) thick restrainer is the optimum choice for this particular system. The dynamic hysteresis loops for this device which illustrate the hysteretic action of the restrainers are shown during a typical test in Figures 29(a) through 29(c). The relative displacements are systematically reduced as the thickness of the restrainer increases. The maximum relative displacement for the 1/4 in. (6.35 mm) device is of the order of 2 in. (50.8 mm).

The influence of the energy-absorbing restrainers on the isolated system is more dramatic. The frame accelerations are reduced and the accelerations at the top of the steam generator are increased. However, for the smaller restrainers, the peak accelerations in the generator occur at the base and these are not significantly increased by the device. The accelerations in the generator are almost uniform from top to bottom when the 1/2 in. (12.7 mm) device is used and these accelerations are roughly the same as those in the frame. The maximum acceleration in the generator when the 1/2 in. (12.7 mm) device is used is only slightly increased for the Taft record over that for the isolated generator with no device. It is possible that the 1/2 in. (12.7 mm) device is too stiff and while producing uniform accelerations over the length of the generator, which is considered beneficial, it increases the accelerations. It may be conjectured that the 1/4 in. (6.35 mm) device would be optimal for this case as well as for the previous case if the levels at which it connects the components were modified. Dynamic hysteresis loops for the energy-absorbing devices when the generator is isolated are shown in Figures 30(a) and 30(b).

5. CONCLUSIONS

The test results can be used to provide insight into the interaction of a large component and the structure within which it is housed. When elastically connected to the frame by the relatively stiff 1 in. thick restrainers, the model of the steam generator most closely represents the connectivity of the prototype. In this case the accelerations experienced by the structure (i.e. the model frame) are less than those experienced when the frame is not interacting with the generator. In contrast, the accelerations experienced by the steam generator when it acts independently of the frame are considerably higher than those experienced when it is elastically connected to the frame by roughly a factor of two but depending on the earthquake input. For all inputs these accelerations are higher than the accelerations experienced by the frame. The acceleration response spectra of the four inputs show progressive increases in the frequency range from 2 Hz to 4 Hz and the increase in the accelerations in the steam generator is due to the increase in its fundamental frequency due to coupling with the structure, whereas the decrease in acceleration in the frame is caused by the decrease in fundamental frequency produced by its coupling to the steam generator. That the response of the frame is less affected in the connected system is due to the fact that its mass is roughly five times that of the component. In practical terms these results indicate that the large component could be analyzed by using input motions computed from structure response assuming the component absent, provided that the influence of the structure on the modal properties of the component were properly accounted for.

The influence of the yielding restrainers on the fixed-base steam generator can also be inferred from the results. In every case introducing yielding has a beneficial effect on the steam generator response. The accelerations experienced by the steam generator with yielding restrainers are for all input signals always less than those for elastic restrainers. These reductions result from the reduction in the fundamental frequency of the generator and from the damping introduced by hysteretic action in the devices. The latter is more likely to be the dominant influence, for the same trend is observable in the structure itself. The frame has lower accelerations when yielding devices are used than when no devices are present and when elastic connections are used. Since the fundamental frequency of the frame increases as the device stiffness decreases due to reduced connectivity to the steam generator, the accelerations in the frame would be expected to increase for these inputs showing that the damping produced by the hysteretic action of the yielding devices is dominant. For all earthquake inputs the test results show that the 1/4 in. thick devices are the optimum choice giving the lowest accelerations on average for both structure and component and also leading to accelerations that are roughly the same in each. This optimum choice might change if the elevations of the energy-absorbing device attachment points were changed. If in a prototype system the location of the collars were not constrained by other factors, the optimum design variables would include location as well as size of the energy-absorbing restrainers.

The test results indicate that the use of base isolation in a large component can be beneficial in reducing the accelerations experienced by the component and the primary structure. The results also indicate that there is a significant advantage in using energy-absorbing restrainers when the component is isolated. The large relative displacements that occur when the component is isolated can be effectively used to dissipate large amounts of seismically induced energy in the composite system leading to reduced response in both component and primary structure.

Even in the case of a large component in a conventional system, the use of yielding restrainers can be beneficial in reducing seismic response. Although the relative displacements are not as great, the energy dissipation can have a significant effect on the response of the system.

The experimental research reported here indicates that base isolation and energy-absorbing restrainers might be a viable retrofit strategy for existing systems with large components having potential seismic hazard.

REFERENCES

[1] C. Plichon, "Hooped Rubber Bearings and Frictional Plates: A Modern Antiseismic Engineering Technique," *Proceedings,* Specialist Meeting on the Anti-Seismic Design of Nuclear Installations, Paris, France (1975); see also: J. Renault, M. Richli, and B. Pavot, "The First Application of Anti-Seismic Friction Bearings: The Kroeberg Nuclear Station," *Annales de l'Institute Technique Batiment des Travaux Publiques,* No. 371, pp. 69-90 (1979).

[2] L. M. Megget, "Analysis and Design of a Base-Isolated Reinforced Concrete Frame Building," *Bulletin of the New Zealand National Society for Earthquake Engineering,* Vol. 11, No. 4 (1978).

[3] G. C. Delfosse, "The GAPEC System: A New Highly Effective Aseismic System," *Proceedings,* The Sixth World Conference on Earthquake Engineering, New Delhi, India (1977).

[4] J. M. Kelly and D. F. Tsztoo, "Earthquake Simulation Testing of a Stepping Frame with Energy-Absorbing Devices," *Bulletin of the New Zealand National Society for Earthquake Engineering,* Vol. 10, No. 4 (1977).

[5] R. I. Skinner, J. M. Kelly, and A. J. Heine, "Hysteretic Dampers for Earthquake-Resistant Structures," *International Journal of Earthquake Engineering and Structural Dynamics,* Vol. 3, pp. 287-296 (1975).

[6] P. N. Spencer, V. F. Zackay, and E. R. Parker, "The Design of Steel Energy-Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety: Volume 1—Summary Report," *Report No. UCB/EERC-79/07,* Earthquake Engineering Research Center, University of California, Berkeley (1979).

[7] S. F. Steimer and W. G. Godden, "The Design of Steel Energy-Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety: Volume 4—Shaking Table Tests of Piping Systems with Energy-Absorbing Restrainers," *Report No. UCB/EERC-80/33,* Earthquake Engineering Research Center, University of California, Berkeley (1980).

[8] J. M. Kelly, M. S. Skinner, and K. E. Beucke, "Experimental Testing of an Energy-Absorbing Base Isolation System," *Report No. UCB/EERC-80/35,* Earthquake Engineering Research Center, University of California, Berkeley (1980).

[9] D. Rea and J. Penzien, "Dynamic Response of a 20' x 20' Shaking Table," *Proceedings,* The Fifth World Conference on Earthquake Engineering, Rome, Italy (1973).

TABLE 1 STATIC PROPERTIES OF RESTRAINERS

DEVICE	YIELD DISPLACEMENT		PLASTIC STRAIN 1-in. DISPLACEMENT	YIELD LOAD	
	[in.]	[mm]	[%]	[lbs]	[kg]
1/8 in.	.32	8.1	.35	80	36.3
2 x 1/8 in.	.32	8.1	.35	160	72.6
1/4 in.	.16	4.1	.70	310	140.6
1/2 in.	.08	2.0	1.40	1125	510.3
1 in.	.04	1.0	2.80	5000	2268.0

TABLE 2 EARTHQUAKE TEST PROGRAM

EL CENTRO

SPAN		BASE	ENERGY-ABS. DEV.	TABLE ACCLN	
H	V			H	V
100	100	FB	0	.221	.279
100	100	FB	2 x 1/8"	.229	.279
100	100	FB	1/4"	.237	.263
100	100	FB	1"	.230	.274
100	100	RB	0	.264	.263
100	100	RB	2 x 1/8"	.234	.264
100	100	RB	1/4"	.228	.281
100	100	RB	1"	.247	.287
100	0	FB	0	.262	0
100	0	FB	1/8"	.259	0
100	0	FB	2 x 1/8"	.249	0
100	0	FB	1/4"	.256	0
100	0	FB	1/2"	.264	0
100	0	FB	1"	.258	0
100	0	RB	0	.239	0
50	0	RB	1/8"	.129	0
100	0	RB	1/8"	.256	0
100	0	RB	2 x 1/8"	.247	0
100	0	RB	1/4"	.251	0
100	0	RB	1/2"	.230	0
200	0	FB	0	.607	0
250	0	FB	1/8"	.741	0
200	0	RB	0	.535	0
250	0	RB	0	.785	0
250	0	FB	0	.801	0

TABLE 2 (continued)

PARKFIELD

SPAN H	SPAN V	BASE	ENERGY-ABS. DEV.	TABLE ACCLN H	TABLE ACCLN V
100	0	FB	0	.134	0
100	0	FB	1/8"	.146	0
100	0	FB	2 x 1/8"	.152	0
100	0	FB	1/4"	.140	0
100	0	FB	1/2"	.123	0
100	0	FB	1"	.138	0
100	0	RB	0	.156	0
100	0	RB	1/8"	.159	0
100	0	RB	2 x 1/8"	.150	0
100	0	RB	1/4"	.152	0
100	0	RB	1/2"	.141	0
240	0	FB	1/8"	.340	0
240	0	FB	2 x 1/8"	.411	0
240	0	FB	1/4"	.340	0
240	0	FB	1/2"	.352	0
240	0	FB	1"	.393	0
240	0	RB	0	.415	0
240	0	RB	1/8"	.425	0
240	0	RB	2 x 1/8"	.438	0
240	0	RB	1/4"	.409	0
240	0	RB	1/2"	.314	0

TABLE 2 (continued)

TAFT

SPAN H	SPAN V	BASE	ENERGY-ABS. DEV.	TABLE ACCLN H	TABLE ACCLN V
100	100	FB	0	.145	.159
100	100	FB	2 x 1/8"	.155	.174
100	100	FB	1/4"	.142	.156
100	100	FB	1"	.138	.097
100	100	RB	0	.135	.099
100	100	RB	2 x 1/8"	.142	.147
100	100	RB	1/4"	.139	.168
100	100	RB	1"	.135	.105
100	0	FB	0	.145	0
100	0	FB	1/8"	.178	0
100	0	FB	2 x 1/8"	.176	0
100	0	FB	1/4"	.141	0
100	0	FB	1/2"	.150	0
100	0	FB	1"	.155	0
100	0	RB	0	.162	0
100	0	RB	1/8"	.150	0
100	0	RB	2 x 1/8"	.149	0
100	0	RB	1/4"	.149	0
100	0	RB	1/2"	.148	0
200	0	FB	1/8"	.273	0
200	0	FB	2 x 1/8"	.297	0
200	0	FB	1/4"	.289	0
200	0	FB	1/2"	.300	0
200	0	FB	1"	.321	0
200	0	RB	0	.333	0
200	0	RB	1/8"	.338	0
200	0	RB	2 x 1/8"	.310	0
200	0	RB	1/4"	.318	0
200	0	RB	1/2"	.292	0

PACOIMA

SPAN H	SPAN V	BASE	ENERGY-ABS. DEV.	TABLE ACCLN H	TABLE ACCLN V
100	0	FB	1/8"	.352	0
100	0	FB	0	.354	0
100	0	FB	2 x 1/8"	.358	0
100	0	FB	1/4"	.349	0
100	0	FB	1/2"	.361	0
100	0	FB	1"	.372	0
0	100	RB	0	0	.408
100	0	RB	0	.347	0
100	0	RB	1/8"	.349	0
100	0	RB	2 x 1/8"	.353	0
100	0	RB	1/4"	.375	0
100	0	RB	1/2"	.350	0
150	0	FB	1/8"	.586	0

TABLE 3
MAXIMUM ACCELERATIONS (g) IN STEAM GENERATOR AND FRAME
EL CENTRO N-S (1940), SPAN 100

a) BASE-ISOLATED SYSTEM

ENERGY ABSORBER	STEAM GENERATOR					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	.326	.224	.129	.061	.053	.141
1/8-in. Device	.307	.214	.149	.091	.079	.146
2 x 1/8-in. Dev.	.308	.249	.196	.144	.142	.202
1/4-in. Device	.376	.300	.237	.229	.183	.220
1/2-in. Device	.586	.570	.572	.606	.633	.694
1-in. Device	.849	.738	.717	.788	.895	1.106

ENERGY ABSORBER	FRAME					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	.239	.857	.796	.906	1.592	1.490
1/8-in. Device	.244	.749	.760	1.077	1.301	1.565
2 x 1/8-in. Dev.	.247	.652	.648	1.001	1.145	1.519
1/4-in. Device	.251	.750	.656	.908	1.167	1.221
1/2-in. Device	.230	.495	.598	.819	.742	1.227
1-in. Device	.247	.421	.554	.693	.596	.877

b) FIXED-BASE SYSTEM

ENERGY ABSORBER	STEAM GENERATOR					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	.286	.246	.325	.443	.562	.689
1/8-in. Device	.261	.227	.332	.457	.573	.704
2 x 1/8-in. Dev.	.246	.261	.356	.465	.592	.695
1/4-in. Device	.247	.227	.312	.517	.639	.831
1/2-in. Device	.251	.449	.655	.911	1.173	1.387
1-in. Device	.260	.421	.752	1.067	1.354	1.659

ENERGY ABSORBER	FRAME					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	.262	.739	.640	.920	1.029	1.272
1/8-in. Device	.259	.727	.771	.910	.985	1.434
2 x 1/8-in. Dev.	.249	.889	.702	1.106	.992	1.313
1/4-in. Device	.256	.521	.646	1.042	.943	1.210
1/2-in. Device	.264	.825	.539	.827	1.008	1.351
1-in. Device	.258	.880	.703	1.024	1.008	1.536

TABLE 4
MAXIMUM ACCELERATIONS (g) IN STEAM GENERATOR AND FRAME
TAFT (1950), SPAN 200

a) BASE-ISOLATED SYSTEM

ENERGY ABSORBER	STEAM					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	.462	.315	.187	.064	.073	.198
1/8-in. Device	.504	.350	.210	.099	.112	.208
2 x 1/8-in. Dev.	.507	.368	.243	.176	.129	.239
1/4-in. Device	.474	.357	.281	.233	.199	.266
1/2-in. Device	.550	.549	.554	.594	.636	.708
1-in. Device	.770	.810	.906	.998	1.124	1.276

ENERGY ABSORBER	FRAME					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	.333	.590	.607	.770	.990	1.078
1/8-in. Device	.338	.567	.591	.728	.781	1.126
2 x 1/8-in. Dev.	.310	.601	.582	.866	.755	1.203
1/4-in. Device	.318	.609	.619	.742	.803	1.179
1/2-in. Device	.259	.575	.479	.653	.701	.900
1-in. Device	.270	.548	.582	.610	.768	1.004

b) FIXED-BASE SYSTEM

ENERGY ABSORBER	STEAM GENERATOR					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	.290	.492	.730	.984	1.296	1.580
1/8-in. Device	.274	.399	.653	.911	1.159	1.402
2 x 1/8-in. Dev.	.300	.436	.638	.865	1.087	1.276
1/4-in. Device	.286	.308	.466	.602	.751	.952
1/2-in. Device	.304	.376	.581	.763	.966	1.203
1-in. Device	.326	.426	.692	.990	1.242	1.521

ENERGY ABSORBER	FRAME					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	.290	.880	.620	.872	.808	.982
1/8-in. Device	.273	.600	.557	.839	.949	1.097
2 x 1/8-in. Dev.	.297	.560	.646	.722	.815	1.070
1/4-in. Device	.260	.689	.614	.815	.774	1.136
1/2-in. Device	.300	.501	.480	.635	.679	.831
1-in. Device	.321	.658	.642	.918	.846	1.138

TABLE 5
MAXIMUM ACCELERATIONS (g) IN STEAM GENERATOR AND FRAME
PARKFIELD N65E (1966), SPAN 240

a) BASE-ISOLATED SYSTEM

ENERGY ABSORBER	STEAM GENERATOR					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	.365	.245	.144	.048	.058	.159
1/8-in. Device	.394	.278	.178	.122	.095	.183
2 x 1/8-in. Dev.	.446	.343	.257	.216	.180	.268
1/4-in. Device	.472	.398	.301	.255	.202	.305
1/2-in. Device	.849	.810	.727	.708	.643	.742

ENERGY ABSORBER	FRAME					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	.415	.977	1.142	1.314	1.319	1.621
1/8-in. Device	.425	.738	1.008	1.131	1.328	1.844
2 x 1/8-in. Dev.	.438	.845	.873	1.333	1.300	1.501
1/4-in. Device	.409	.757	.879	1.059	1.306	1.722
1/2-in. Device	.314	1.108	.788	.835	.990	1.643

b) FIXED-BASE SYSTEM

ENERGY ABSORBER	STEAM GENERATOR					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	.348	.336	.487	.686	.854	1.066
1/8-in. Device	.369	.248	.405	.555	.701	.843
2 x 1/8-in. Dev.	.418	.240	.362	.532	.691	.931
1/4-in. Device	.339	.307	.510	.768	.961	1.211
1/2-in. Device	.374	.608	.892	1.238	1.583	1.846
1-in. Device	.420	.708	1.079	1.476	1.846	2.261

ENERGY ABSORBER	FRAME					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	.322	.686	.854	.962	1.099	1.258
1/8-in. Device	.340	.975	.814	.956	1.198	1.646
2 x 1/8-in. Dev.	.411	.952	.861	1.062	1.130	1.595
1/4-in. Device	.340	.671	.823	.929	1.207	1.437
1/2-in. Device	.352	.923	.747	.985	1.074	1.456
1-in. Device	.393	.819	.789	1.163	1.439	1.339

TABLE 6

MAXIMUM DISPLACEMENTS OF STEAM GENERATOR RELATIVE TO FRAME
EL CENTRO N-S (1940), SPAN 100

a) BASE-ISOLATED SYSTEM

ENERGY ABSORBING DEVICE	DISPL. AT GENERATOR RELATIVE TO FRAME [in.] $\frac{minimum + maximum}{2}$					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	1.196	.934	.936	1.007	1.701	1.951
1/8-in. Device	1.254	.981	1.050	1.281	1.984	2.567
2 x 1/8-in. Dev.	1.159	1.007	1.126	1.438	1.928	2.317
1/4-in. Device	1.003	.944	1.015	1.197	1.653	2.093
1/2-in. Device	.718	.646	.827	1.062	1.354	1.664
1-in. Device	.727	.593	.733	1.016	1.361	1.812

b) FIXED-BASE SYSTEM

ENERGY ABSORBING DEVICE	DISPL. AT GENERATOR RELATIVE TO FRAME [in.] $\frac{minimum + maximum}{2}$					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	0	.758	1.435	2.088	2.791	3.482
1/8-in. Device	0	.709	1.298	1.907	2.521	3.130
2 x 1/8-in. Dev.	0	.652	1.174	1.746	2.532	3.132
1/4-in. Device	0	.412	.779	1.151	1.510	1.879
1/2-in. Device	0	.207	.373	.572	.779	.994
1-in. Device	0	.222	.373	.567	.781	1.089

TABLE 7

MAXIMUM DISPLACEMENTS OF STEAM GENERATOR RELATIVE TO FRAME
TAFT (1950), SPAN 200

a) BASE-ISOLATED SYSTEM

ENERGY ABSORBING DEVICE	DISPL. AT GENERATOR RELATIVE TO FRAME [in.] $\frac{minimum + maximum}{2}$					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	.774	.597	.646	.810	1.123	1.437
1/8-in. Device	.832	.876	1.074	1.294	1.664	1.998
2 x 1/8-in. Dev.	.704	.596	.642	.826	1.211	1.496
1/4-in. Device	.777	.625	.650	.798	1.057	1.253
1/2-in. Device	.810	.712	.738	.838	.972	1.161
1-in. Device	.968	.728	.701	.881	1.230	1.589

b) FIXED-BASE SYSTEM

ENERGY ABSORBING DEVICE	DISPL. AT GENERATOR RELATIVE TO FRAME [in.] $\frac{minimum + maximum}{2}$					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	0	.352	.690	1.023	1.361	1.670
1/8-in. Device	0	.355	.687	1.032	1.344	1.649
2 x 1/8-in. Dev.	0	.355	.676	1.033	1.503	1.851
1/4-in. Device	0	.374	.726	1.085	1.415	1.718
1/2-in. Device	0	.276	.514	.773	1.053	1.325
1-in. Device	0	.211	.315	.460	.717	.934

TABLE 8

MAXIMUM DISPLACEMENTS OF STEAM GENERATOR RELATIVE TO FRAME
PARKFIELD N65E (1966), SPAN 240

a) BASE-ISOLATED SYSTEM

ENERGY ABSORBING DEVICE	DISPL. AT GENERATOR RELATIVE TO FRAME [in.] $\frac{minimum + maximum}{2}$					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	.842	.894	1.259	1.664	2.101	2.682
1/8-in. Device	.895	1.041	1.459	1.896	2.505	2.961
2 x 1/8-in. Dev.	1.051	1.064	1.419	1.806	2.420	2.975
1/4-in. Device	1.182	1.152	1.301	1.474	2.025	2.473
1/2-in. Device	1.345	1.188	1.150	1.178	1.354	1.653

b) FIXED-BASE SYSTEM

ENERGY ABSORBING DEVICE	DISPL. AT GENERATOR RELATIVE TO FRAME [in.] $\frac{minimum + maximum}{2}$					
	BASE	1st FL	2nd FL	3rd FL	4th FL	5th FL
No Device	0	.484	.911	1.345	1.760	2.207
1/8-in. Device	0	.423	.838	1.257	1.656	2.047
2 x 1/8-in. Dev.	0	.464	.883	1.327	1.921	2.355
1/4-in. Device	0	.554	1.052	1.557	2.036	2.501
1/2-in. Device	0	.424	.757	1.130	1.505	1.898
1-in. Device	0	.357	.570	.844	1.017	1.636

TABLE 9

MAXIMUM FORCES AND DISPLACEMENTS AT ENERGY-ABSORBING DEVICES
EL CENTRO N-S (1940), SPAN 100

a) BASE-ISOLATED SYSTEM

ENERGY ABSORBING DEVICE	FORCES, DISPL. AT ENERGY-ABSORBING DEVICES 2nd FLOOR		4th FLOOR	
	FORCE [lbs]	DISPL [in]	FORCE [lbs]	DISPL [in]
No Device	0	1.234	0	2.074
1/8-in. Device	215	1.184	240	1.887
2 x 1/8-in. Dev.	496	1.595	589	2.325
1/4-in. Device	678	1.519	818	2.440
1/2-in. Device	2569	.930	3660	1.266
1-in. Device	4494	.819	5473	1.504

b) FIXED-BASE SYSTEM

ENERGY ABSORBING DEVICE	FORCES, DISPL. AT ENERGY-ABSORBING DEVICES 2nd FLOOR		4th FLOOR	
	FORCE [lbs]	DISPL. [in]	FORCE [lbs]	DISPL. [in]
No Device	0	1.276	0	3.136
1/8-in. Device	178	1.027	202	2.467
2 x 1/8-in. Dev.	413	.981	546	2.287
1/4-in. Device	593	.737	746	1.796
1/2-in. Device	1740	.370	2790	.933
1-in. Device	2304	.354	3874	.900

TABLE 10

MAXIMUM FORCES AND DISPLACEMENTS AT ENERGY-ABSORBING DEVICES
TAFT (1950), SPAN 200

a) BASE-ISOLATED SYSTEM

ENERGY ABSORBING DEVICE	FORCES, DISPL. AT ENERGY-ABSORBING DEVICES 2nd FLOOR		4th FLOOR	
	FORCE [lbs]	DISPL. [in]	FORCE [lbs]	DISPL. [in]
No Device	0	.646	0	1.319
1/8-in. Device	213	1.443	240	2.476
2 x 1/8-in. Dev.	399	.767	548	1.368
1/4-in. Device	670	.601	691	1.025
1/2-in. Device	2541	.745	3065	1.322
1-in. Device	3786	.738	4817	1.248

b) FIXED-BASE SYSTEM

ENERGY ABSORBING DEVICE	FORCES, DISPL. AT ENERGY-ABSORBING DEVICES 2nd FLOOR		4th FLOOR	
	FORCE [lbs]	DISPL. [in]	FORCE [lbs]	DISPL. [in]
No Device	0	.605	0	1.509
1/8-in. Device	128	.589	189	1.464
2 x 1/8-in. Dev.	376	.585	502	1.443
1/4-in. Device	697	.624	750	1.590
1/2-in. Device	2492	.498	2835	1.257
1-in. Device	2256	.314	4441	.635

TABLE 11

MAXIMUM FORCES AND DISPLACEMENTS AT ENERGY-ABSORBING DEVICES
PARKFIELD N65E (1966), SPAN 240

a) BASE-ISOLATED SYSTEM

ENERGY ABSORBING DEVICE	FORCES, DISPL. AT ENERGY-ABSORBING DEVICES			
	2nd FLOOR		4th FLOOR	
	FORCE [lbs]	DISPL. [in]	FORCE [lbs]	DISPL. [in]
No Device	0	1.401	0	2.543
1/8-in. Device	246	2.049	402	3.043
2 x 1/8-in. Dev.	556	2.130	710	3.427
1/4-in. Device	681	1.827	884	2.947
1/2-in. Device	2957	1.520	3219	1.934

b) FIXED-BASE SYSTEM

ENERGY ABSORBING DEVICE	FORCES, DISPL. AT ENERGY-ABSORBING DEVICES			
	2nd FLOOR		4th FLOOR	
	FORCE [lbs]	DISPL. [in]	FORCE [lbs]	DISPL. [in]
No Device	0	.848	0	2.087
1/8-in. Device	152	.756	174	1.918
2 x 1/8-in. Dev.	362	.852	493	2.049
1/4-in. Device	697	.890	825	2.297
1/2-in. Device	2531	.703	3374	1.764
1-in. Device	3271	.527	5260	1.273

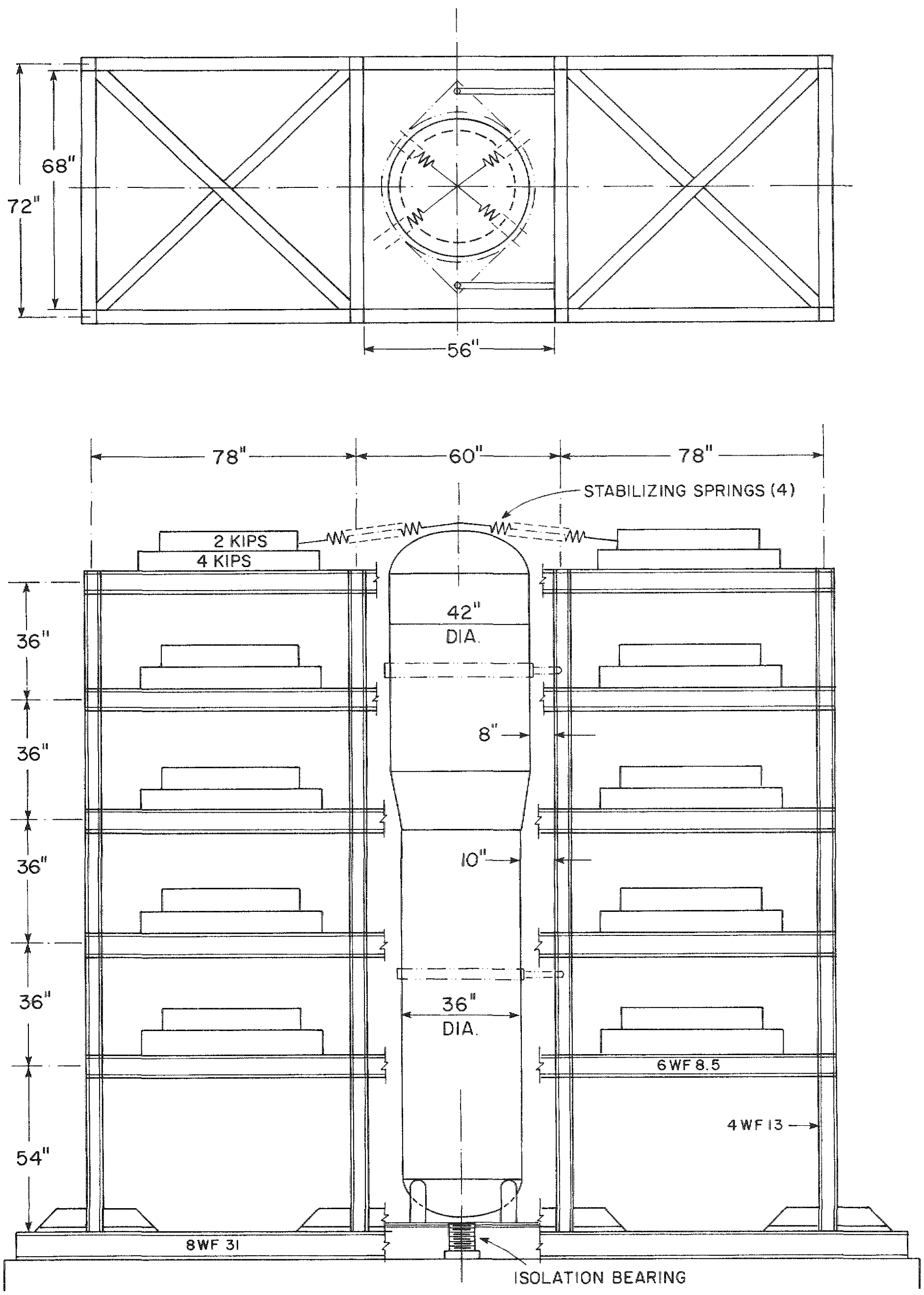

FIGURE 1 SCHEMATIC DRAWING OF MODEL OF COMBINED SYSTEM

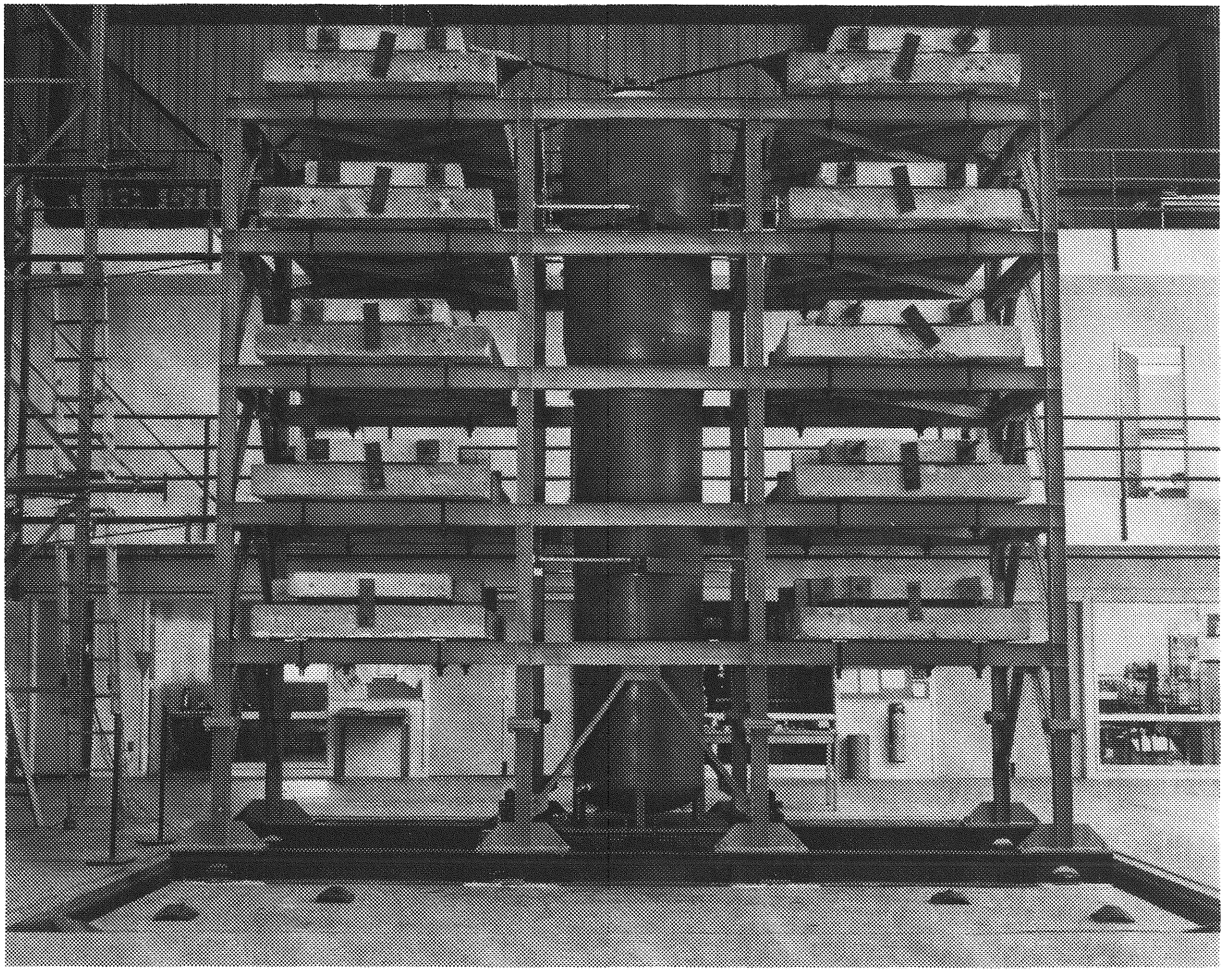

FIGURE 2 MODEL MOUNTED ON THE SHAKING TABLE AT EERC

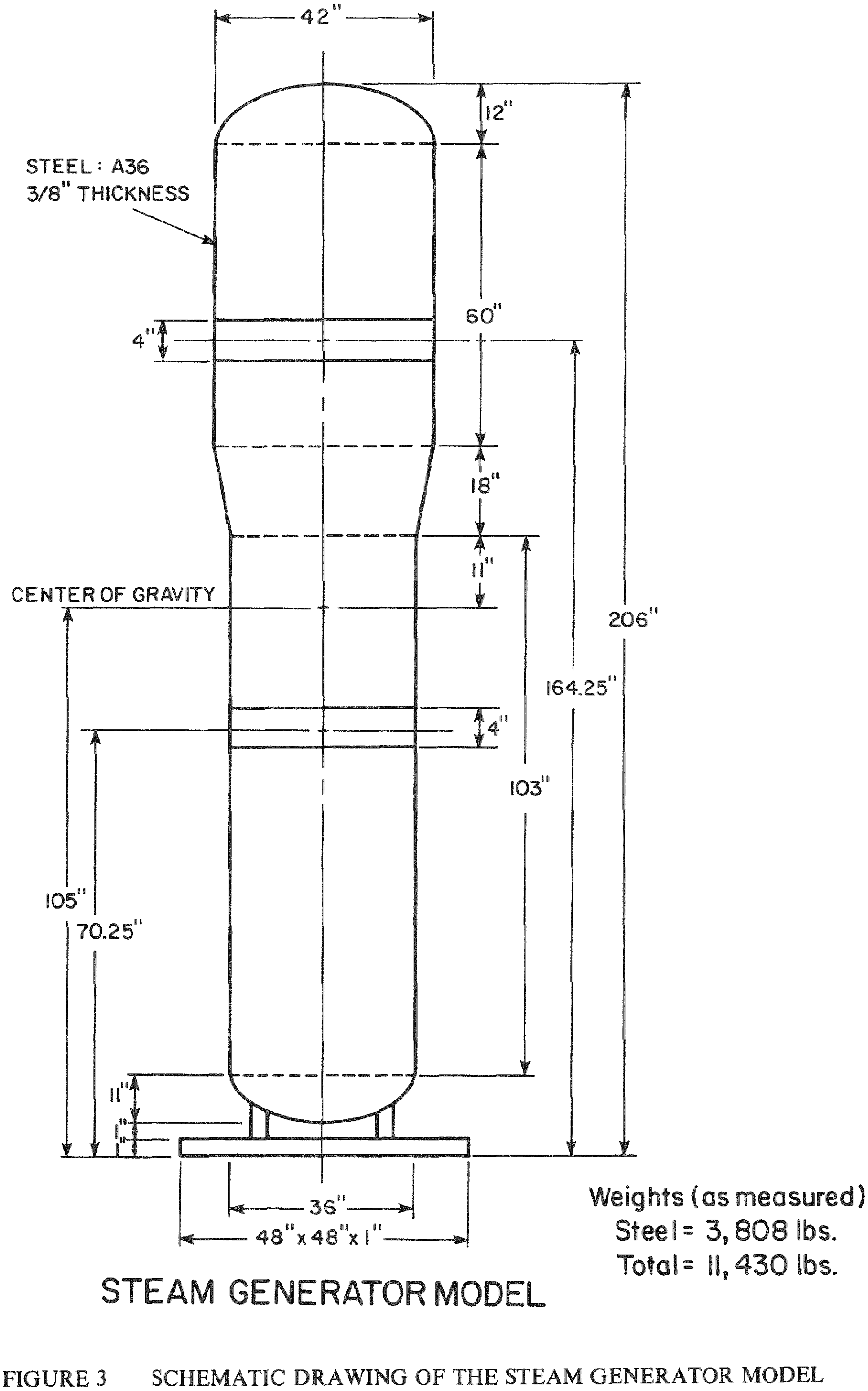

FIGURE 3 SCHEMATIC DRAWING OF THE STEAM GENERATOR MODEL

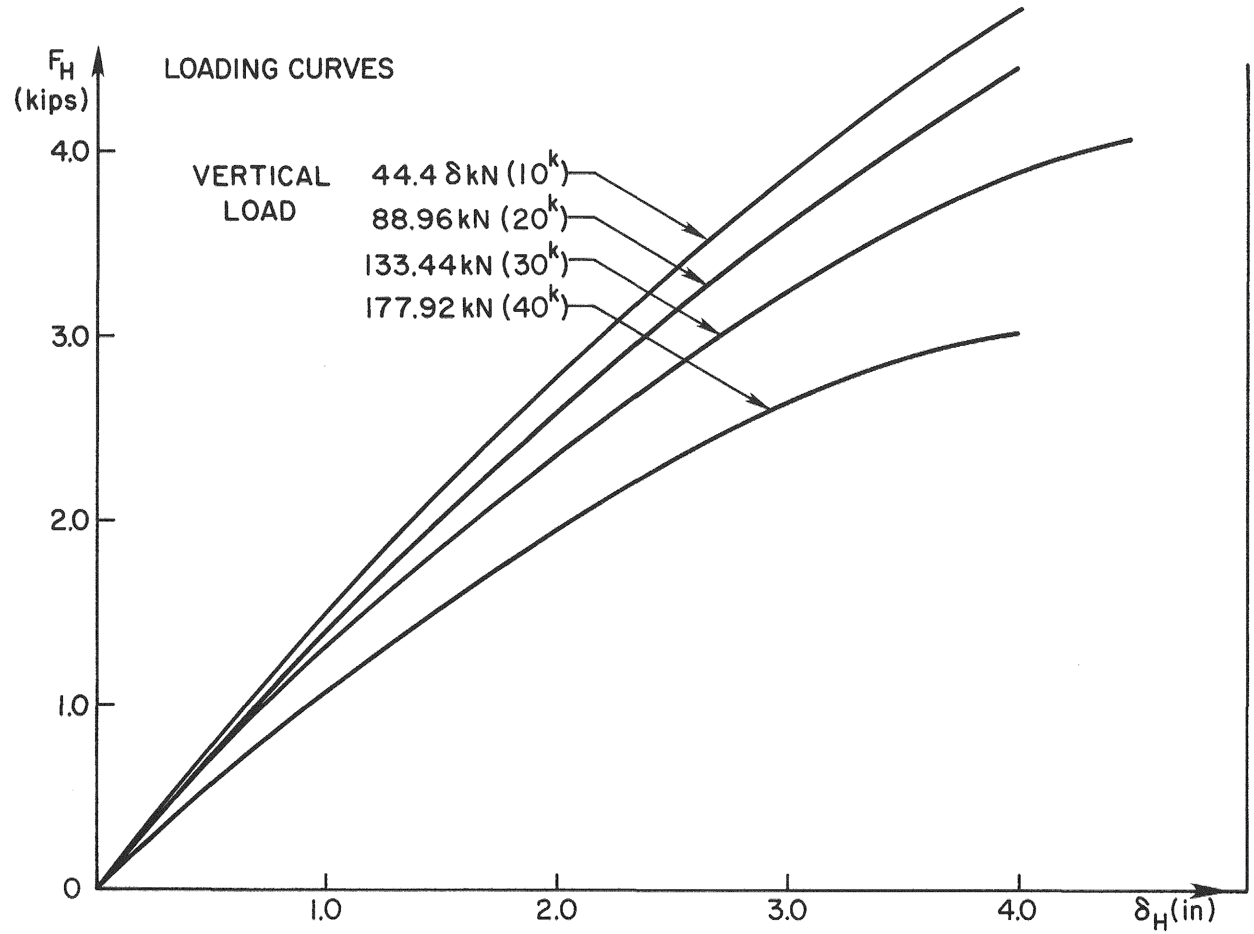

FIGURE 4 STIFFNESS CHARACTERISTICS OF THE RUBBER ISOLATION BEARINGS UNDER STATIC LOADING

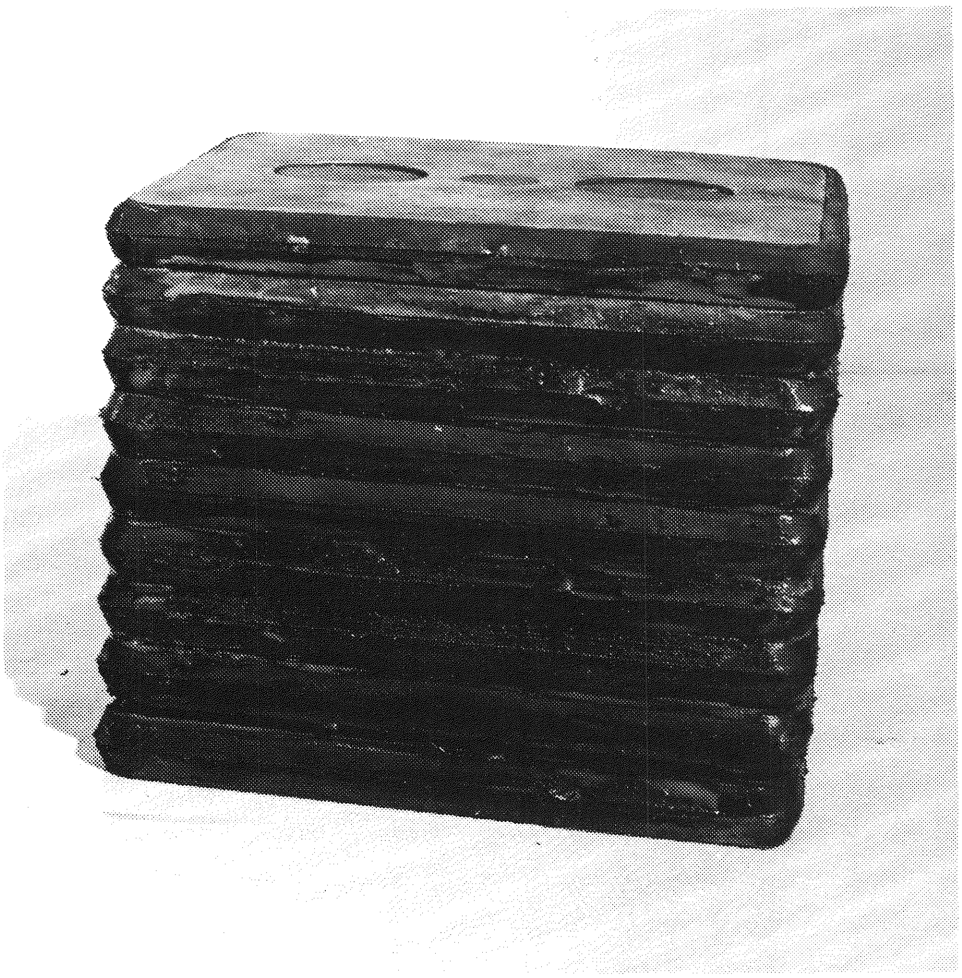

FIGURE 5 MULTILAYER ELASTOMERIC ISOLATION BEARING

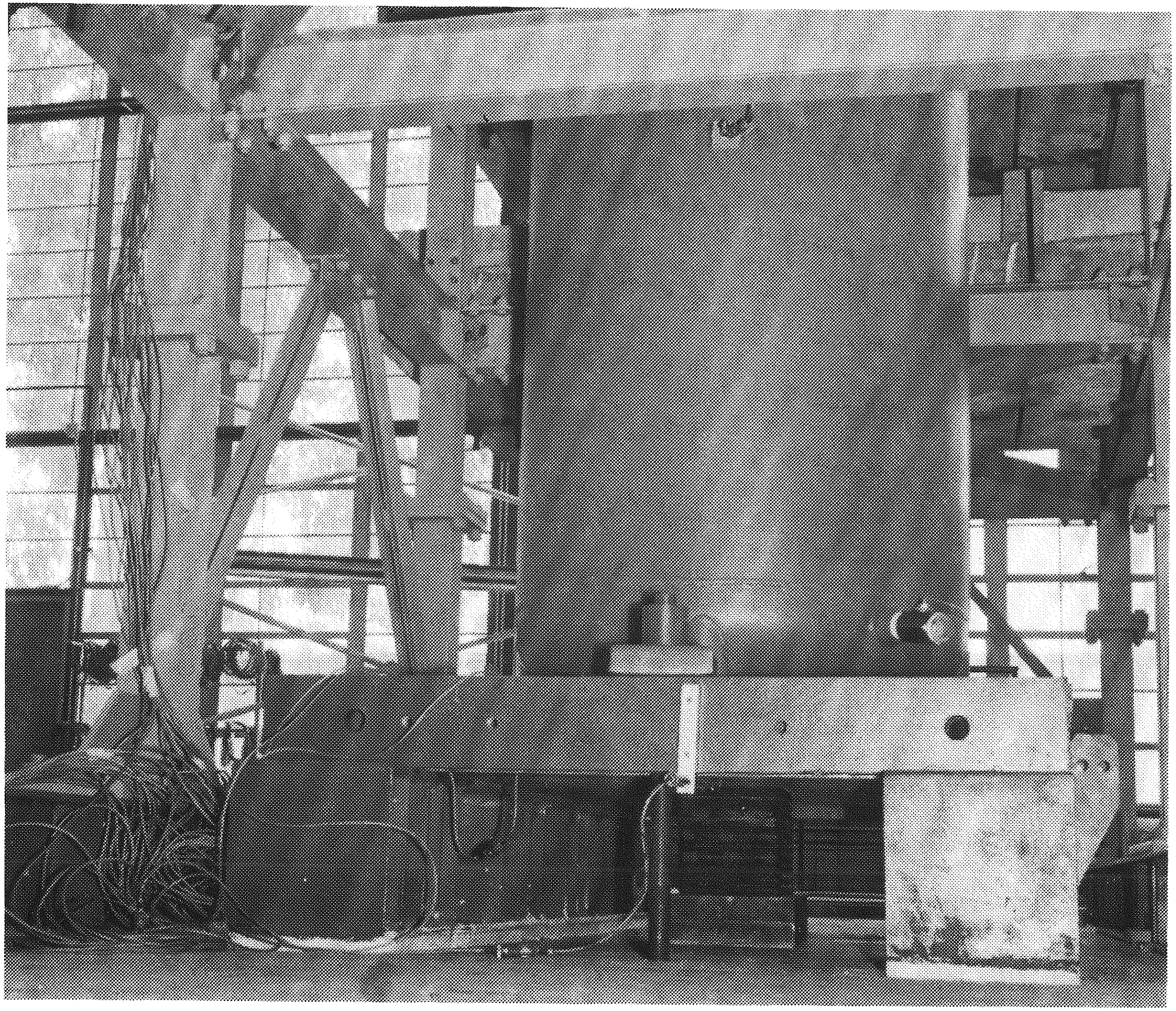

FIGURE 6 ISOLATION BEARING INSTALLED UNDER THE STEAM GENERATOR MODEL

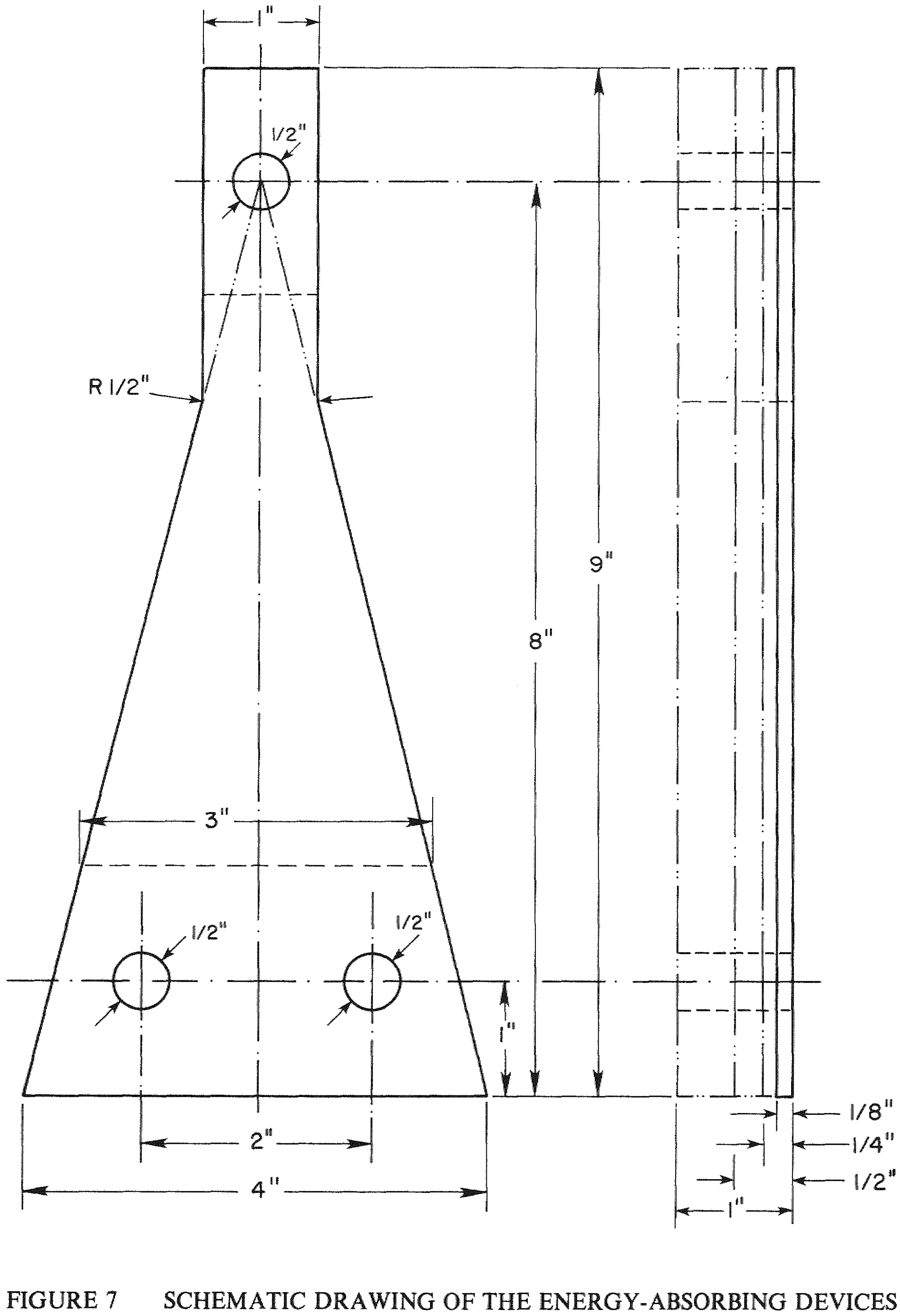

FIGURE 7 SCHEMATIC DRAWING OF THE ENERGY-ABSORBING DEVICES

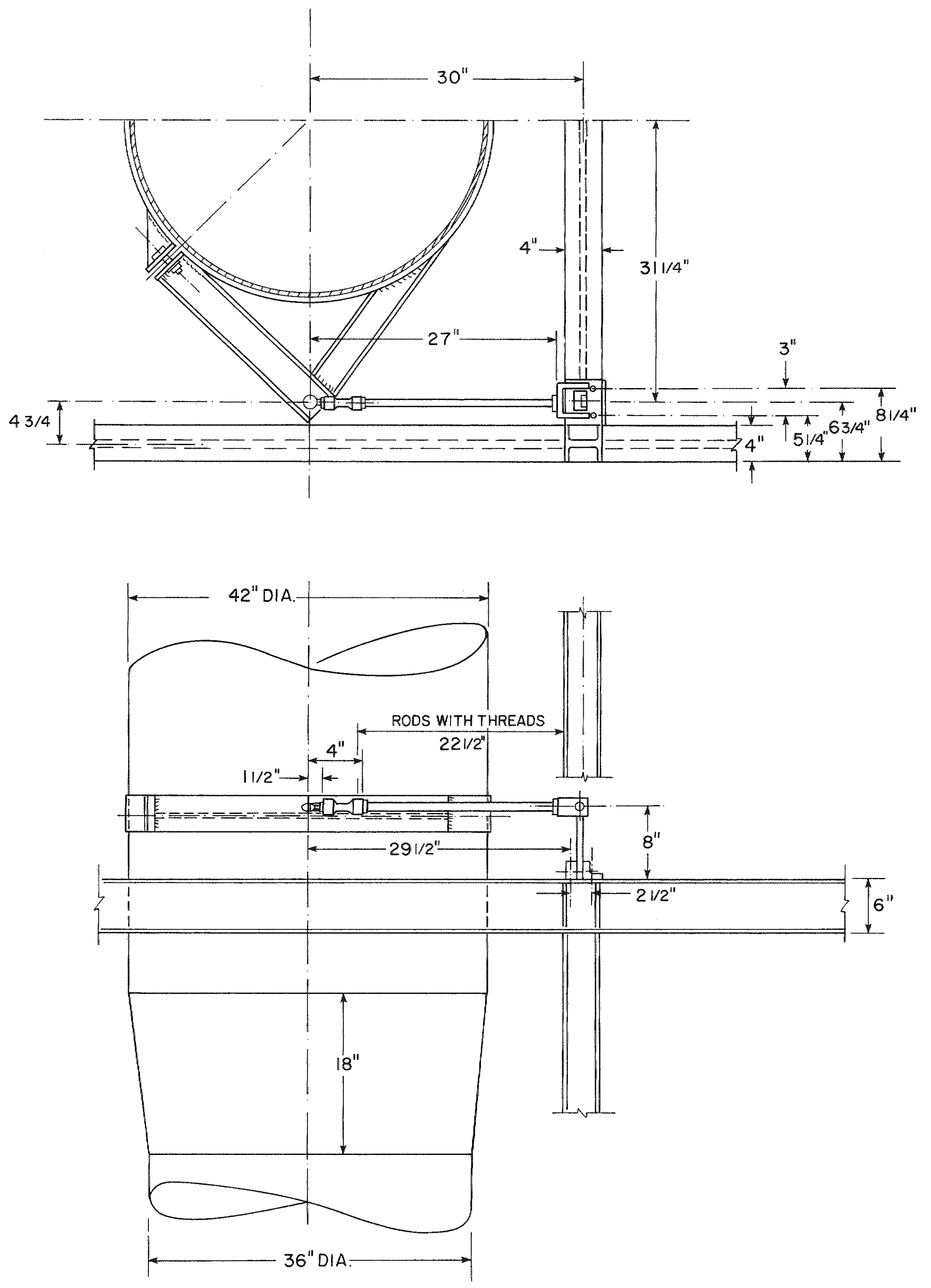

FIGURE 8 SCHEMATIC DRAWING OF THE CONNECTION OF THE ENERGY-ABSORBING DEVICES TO THE STEAM GENERATOR MODEL

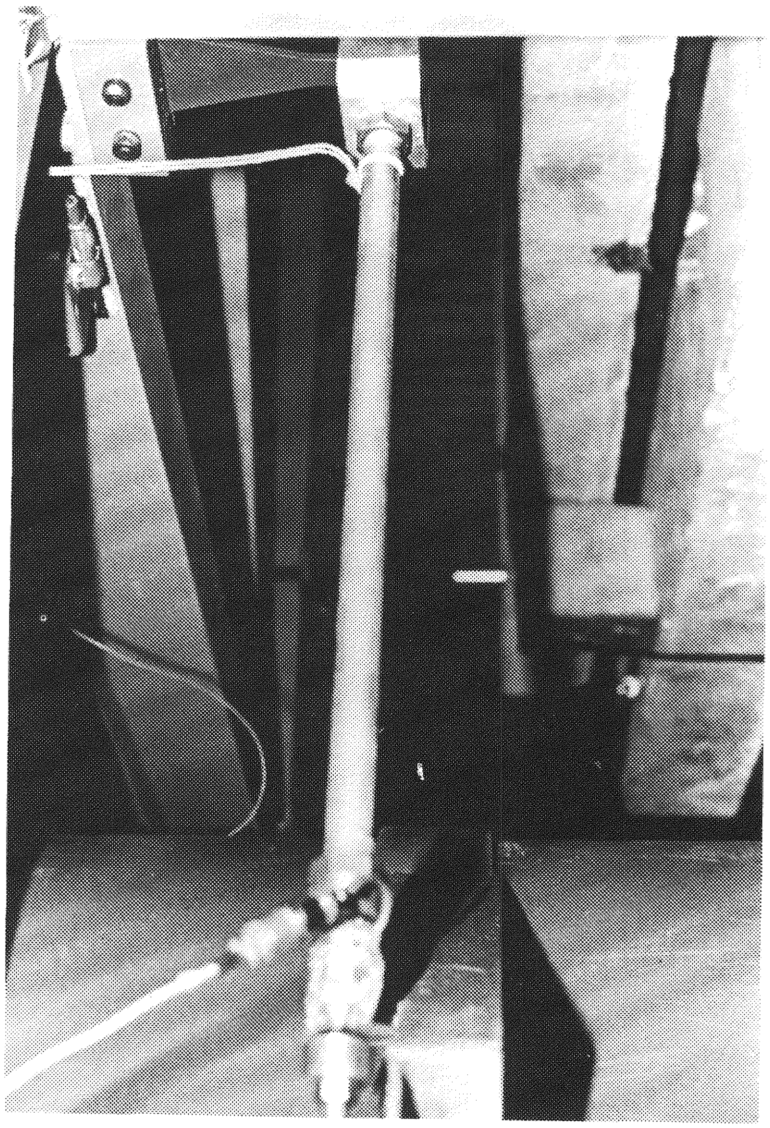

FIGURE 9 ENERGY-ABSORBING DEVICES INSTALLED AT THE UPPER LEVEL

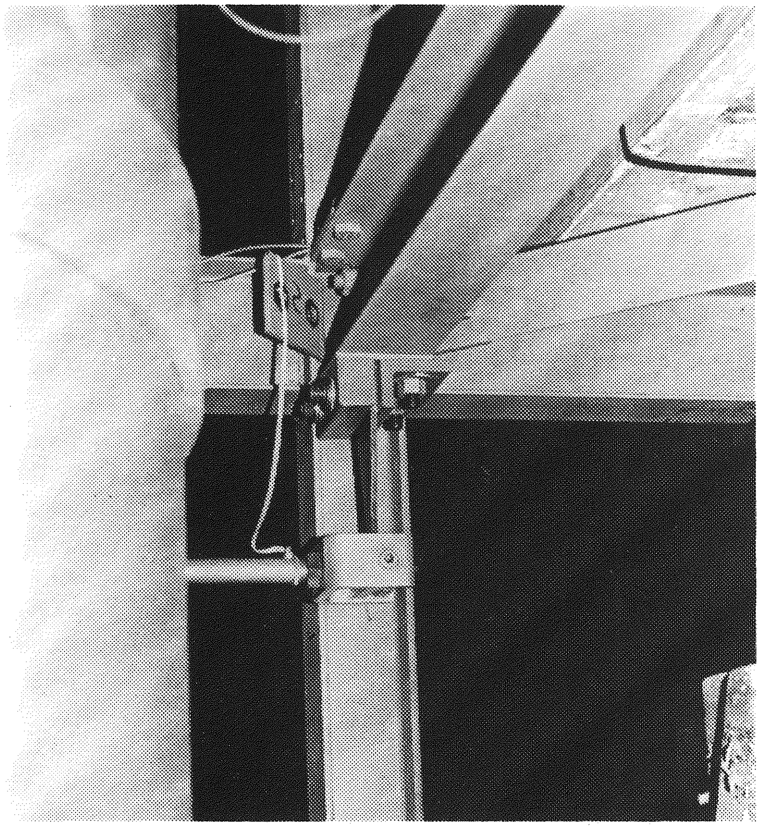

FIGURE 10 ENERGY-ABSORBING DEVICES INSTALLED AT THE LOWER LEVEL

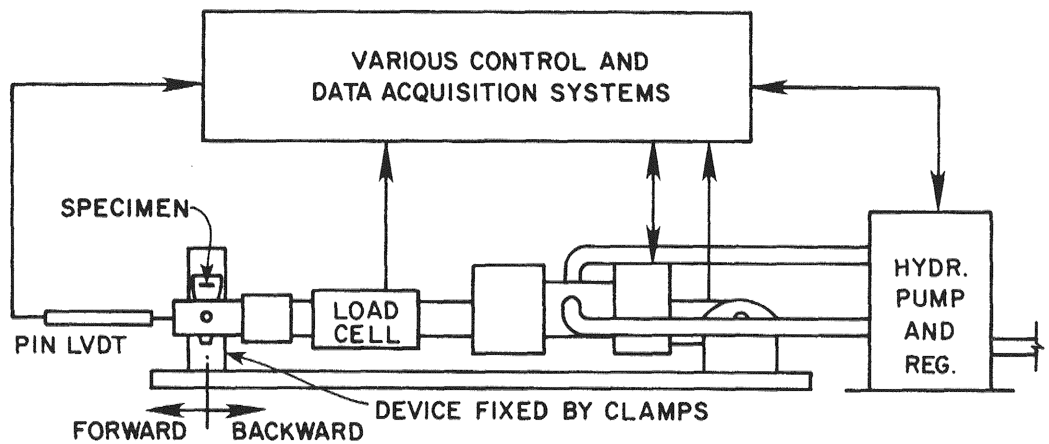

FIGURE 11 SCHEMATIC DIAGRAM OF THE TEST SET-UP FOR STATIC TESTING OF THE ENERGY-ABSORBING DEVICES

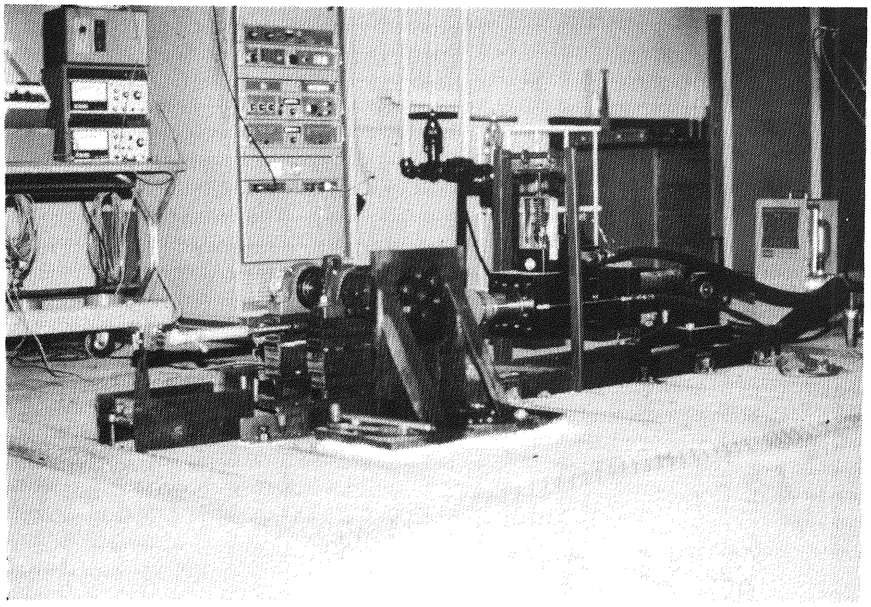

FIGURE 12 TEST SET-UP FOR STATIC TESTING OF THE ENERGY-ABSORBING DEVICES

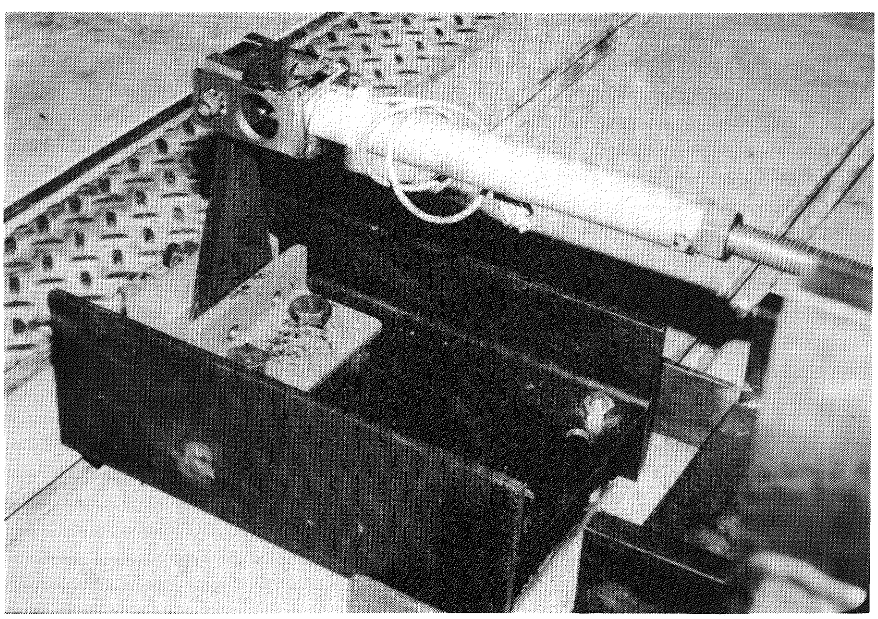

FIGURE 13 ENERGY-ABSORBING DEVICE INSTALLED IN THE TEST RIG

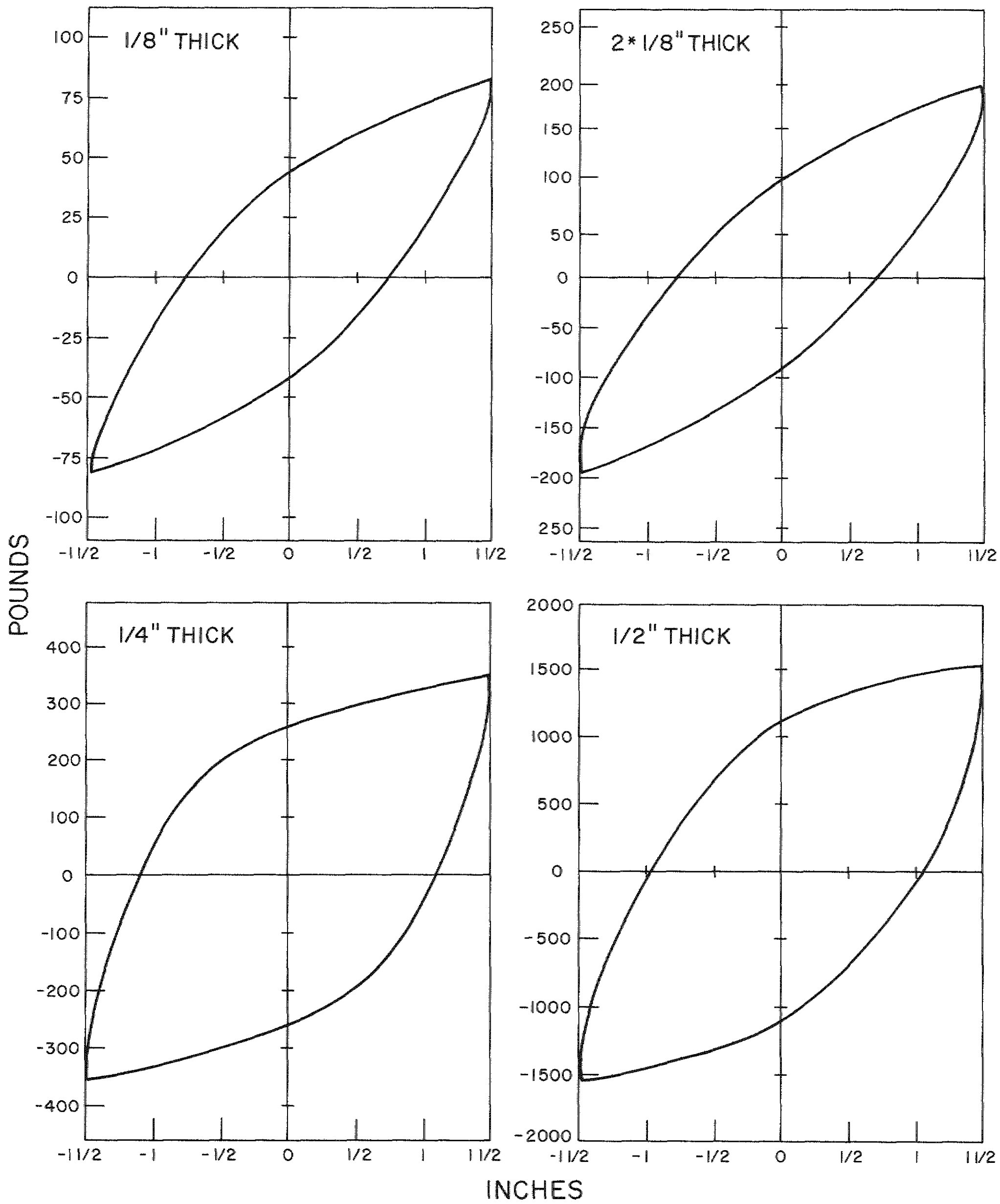

FIGURE 14 STATIC HYSTERESIS LOOPS FOR THE ENERGY-ABSORBING DEVICES USED IN THE TEST SERIES

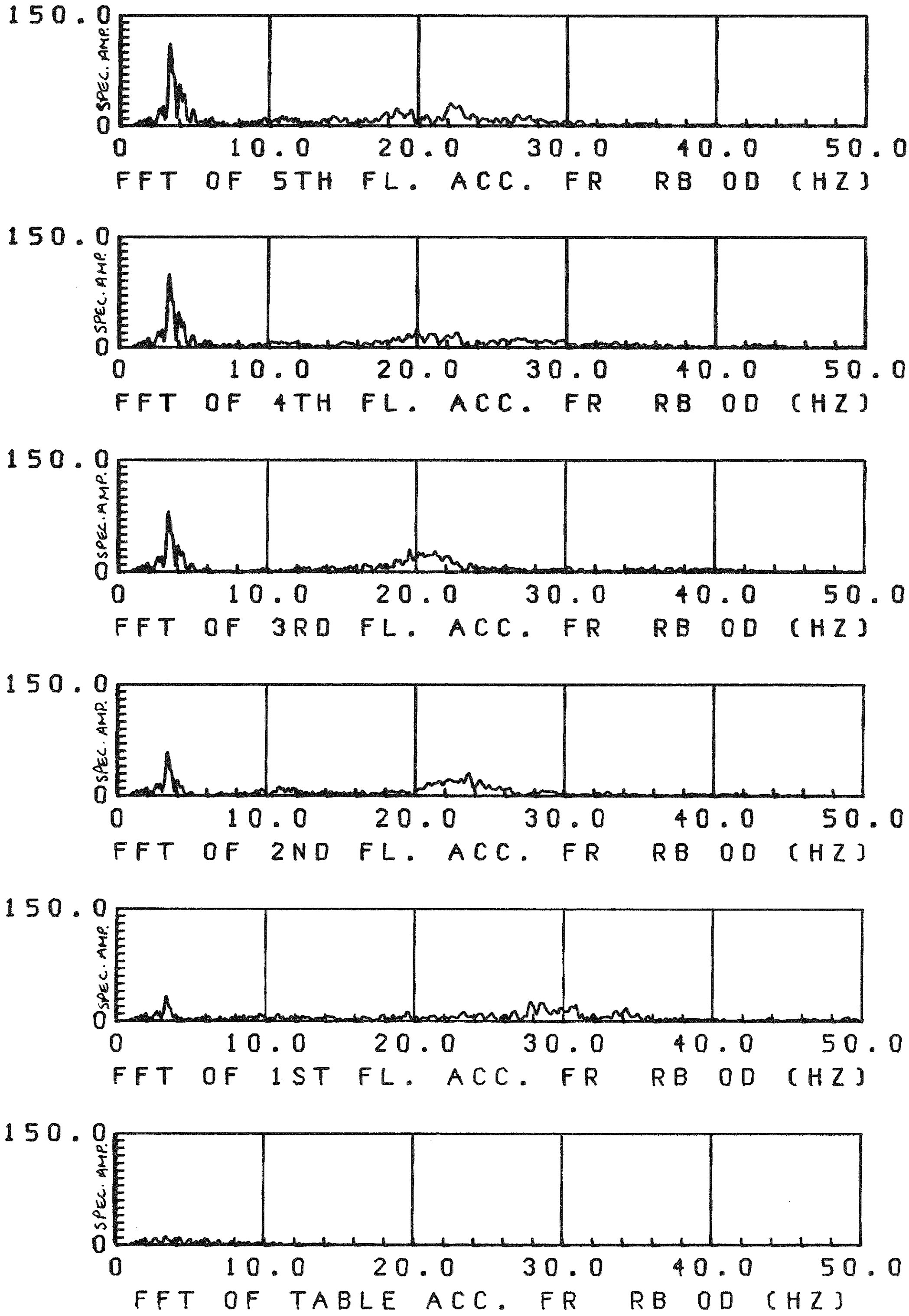

FIGURE 15 FOURIER TRANSFORMS OF FRAME RESPONSE UNDER EL CENTRO INPUT

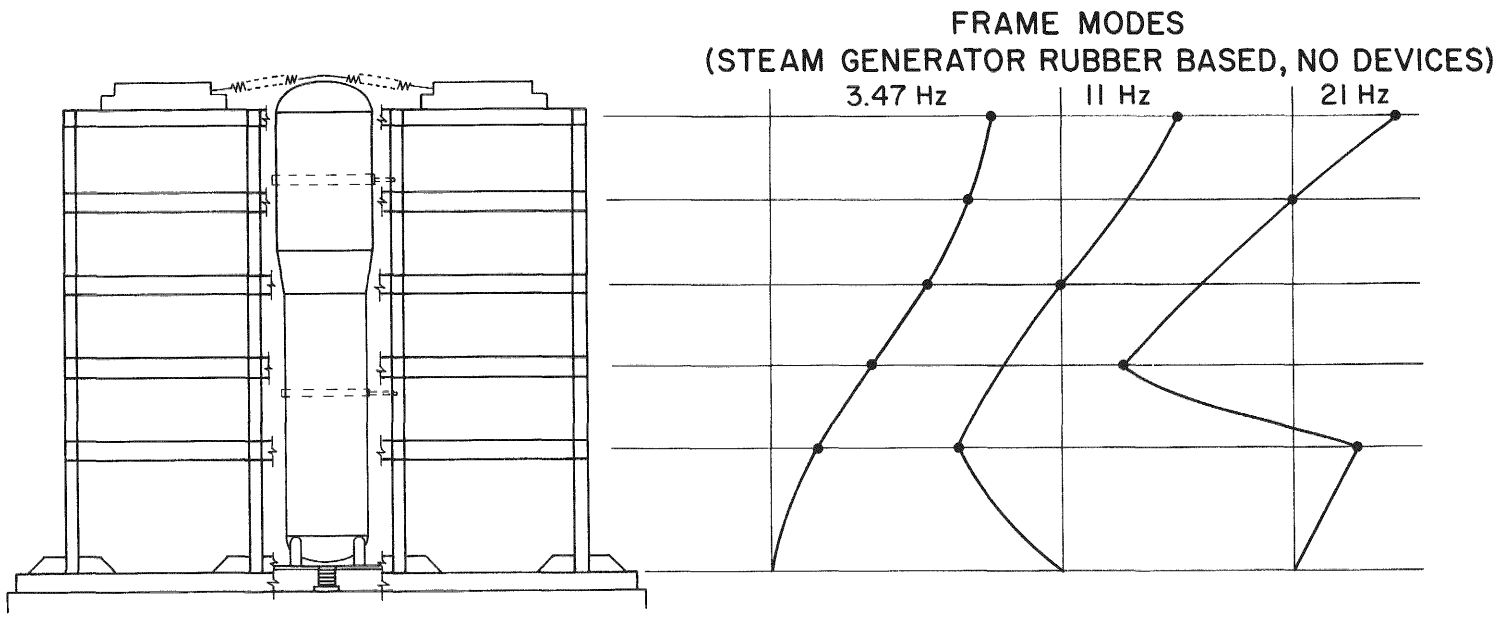

FIGURE 16 ESTIMATE OF MODE SHAPES OF THE FRAME

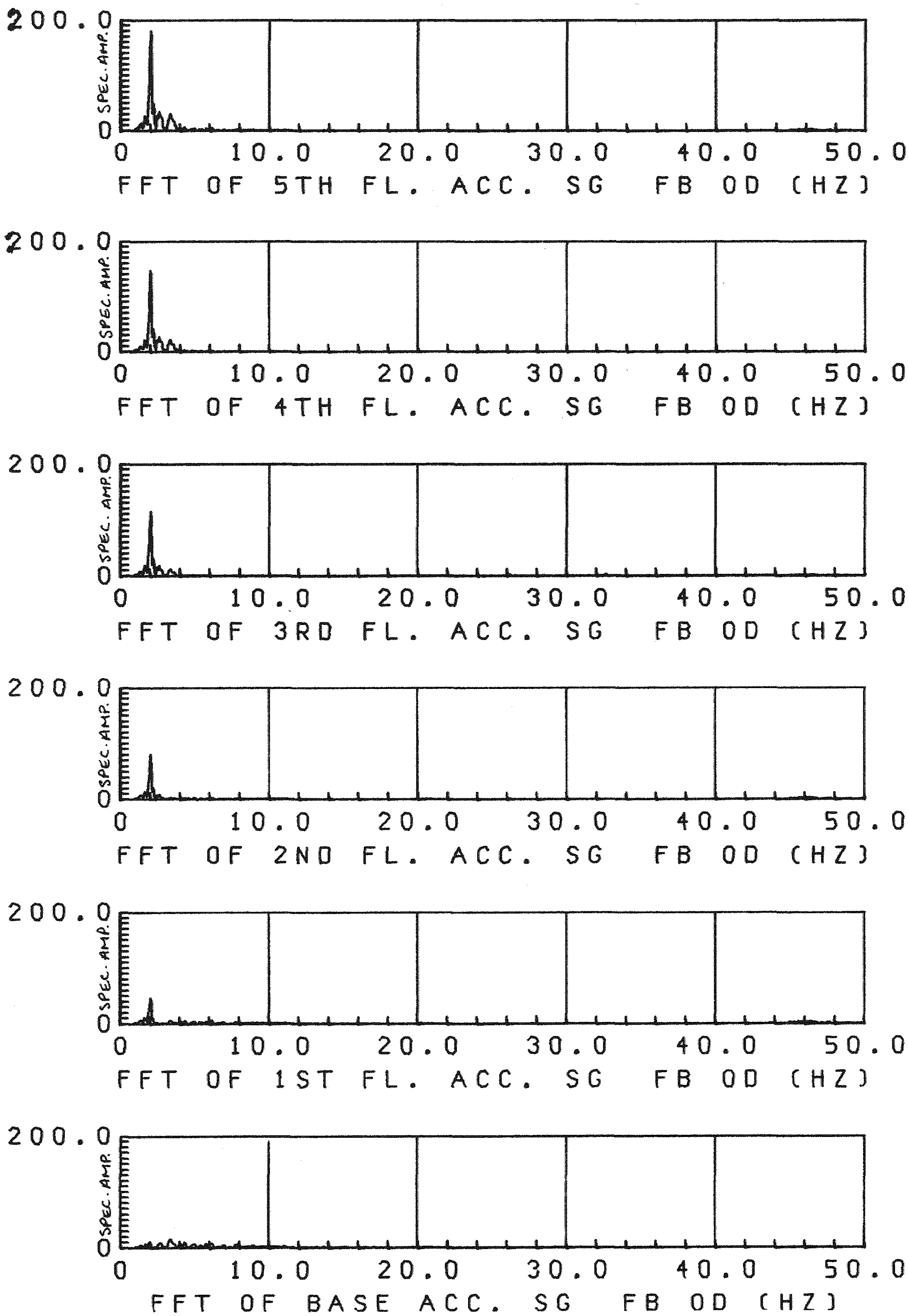

FIGURE 17 FOURIER TRANSFORM OF THE RESPONSE OF THE STEAM GENERATOR MODEL IN THE FIXED-BASE CONDITION

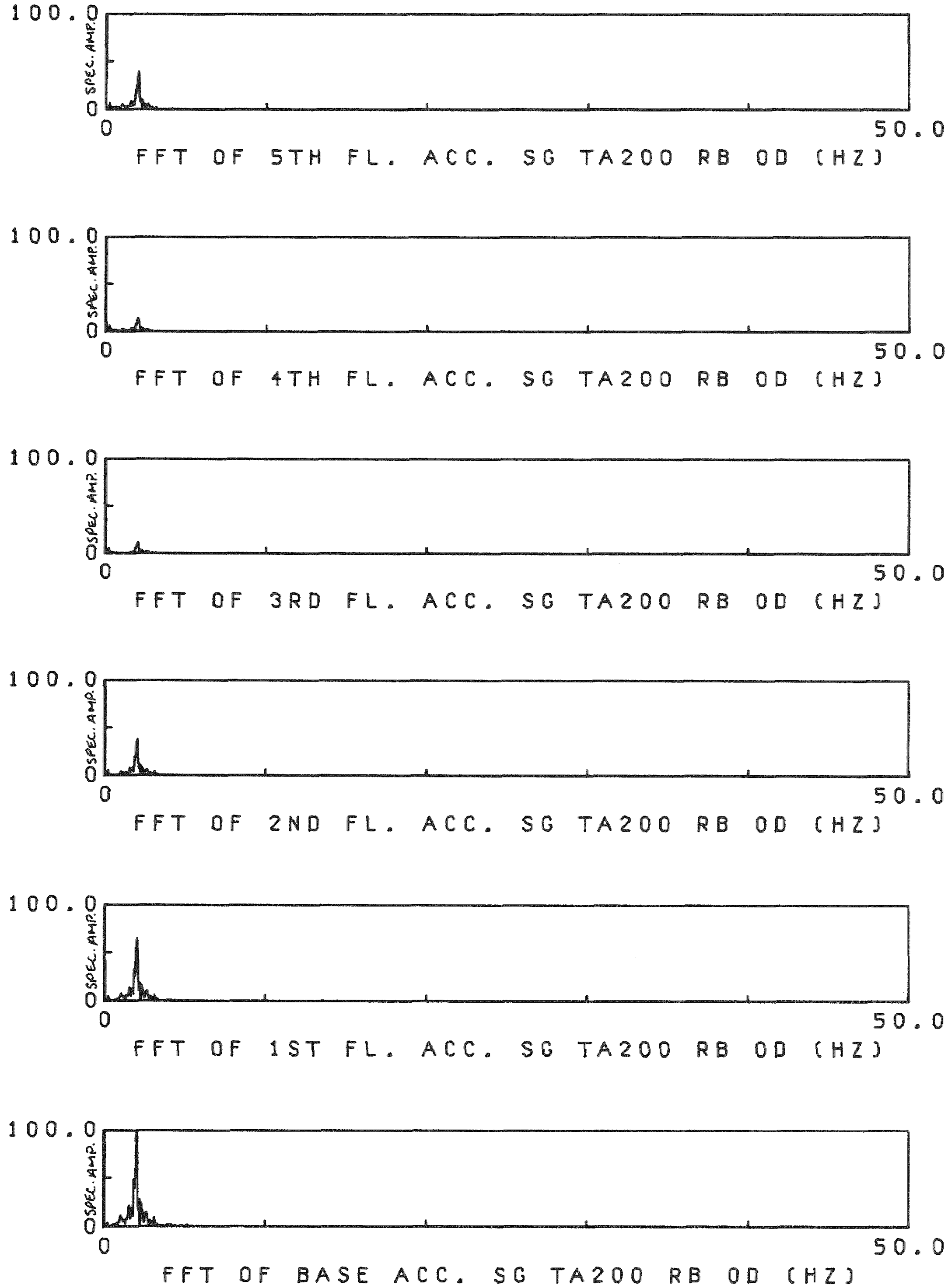

FIGURE 18 FOURIER TRANSFORM OF THE RESPONSE OF THE STEAM GENERATOR MODEL IN THE RUBBER-BASED CONDITION

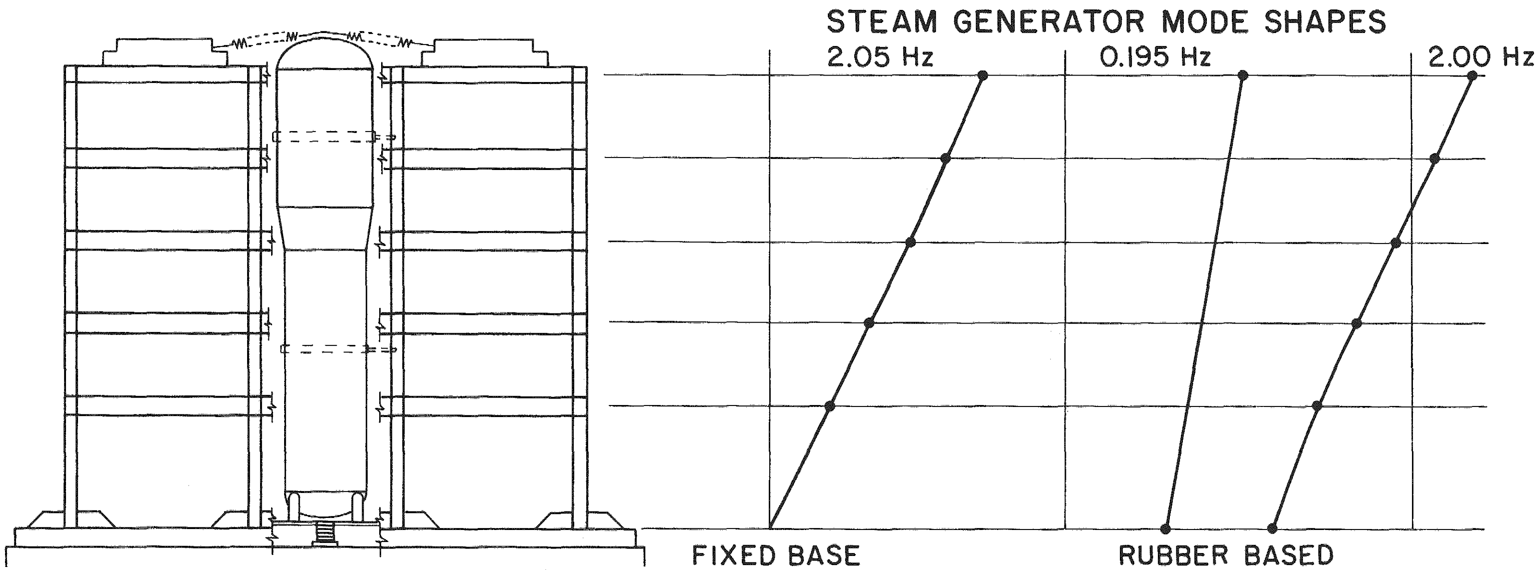

FIGURE 19 ESTIMATE OF MODE SHAPES OF THE STEAM GENERATOR MODEL WHEN ISOLATED AND WHEN FIXED

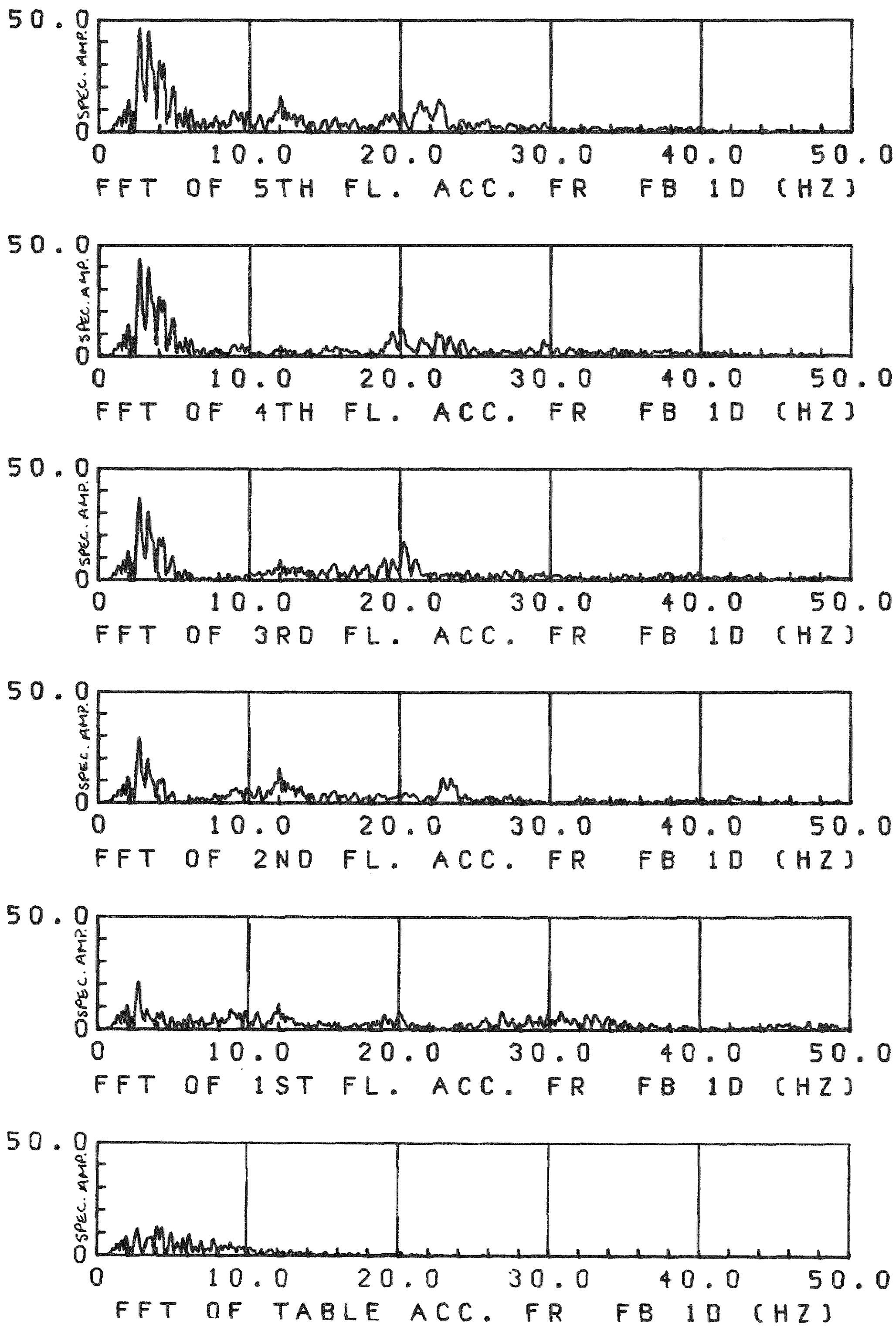

FIGURE 20 FOURIER TRANSFORMS OF THE RESPONSE OF THE FRAME WHEN ELASTICALLY CONNECTED TO THE STEAM GENERATOR MODEL

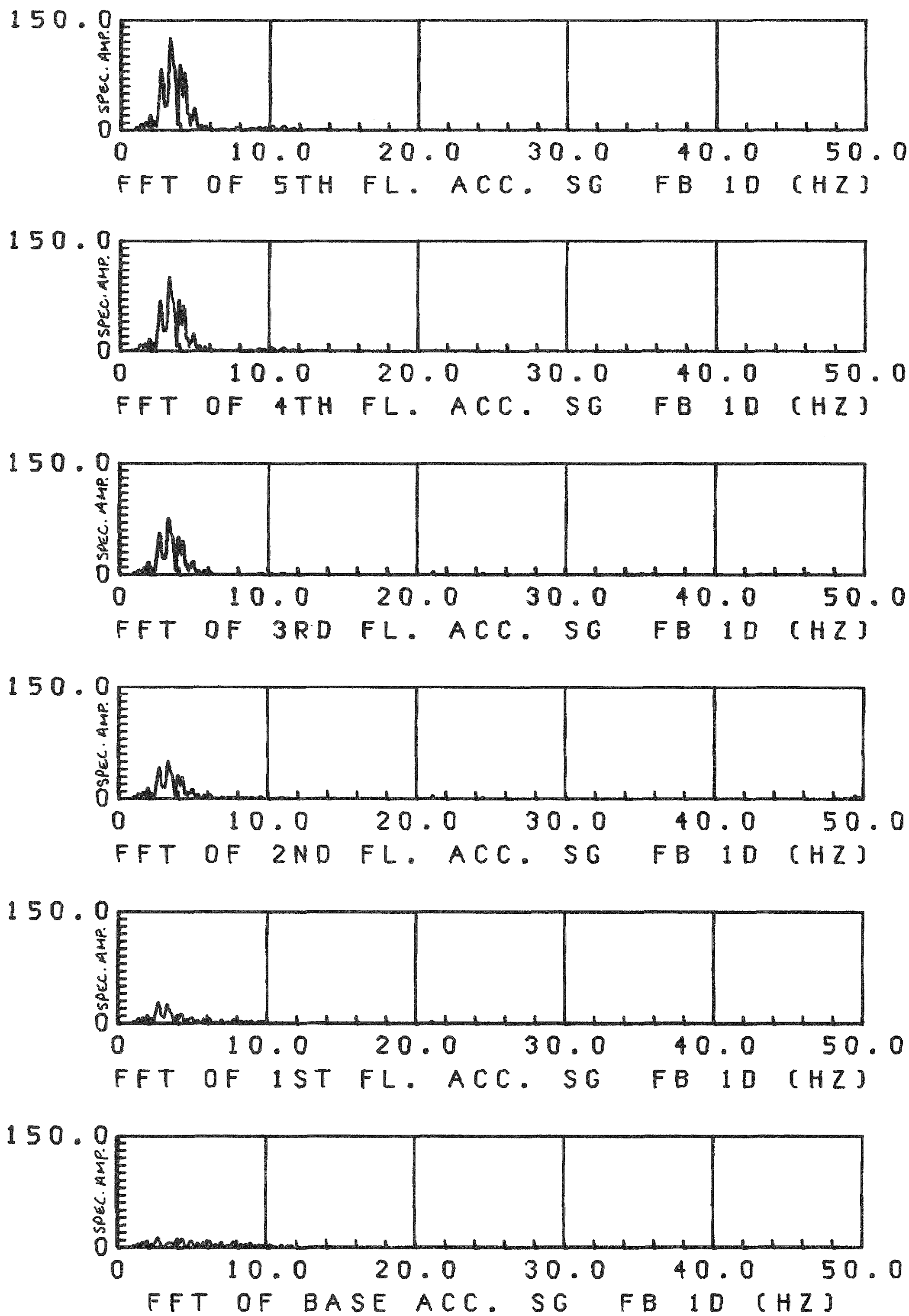

FIGURE 21 FOURIER TRANSFORM OF THE RESPONSE OF THE STEAM GENERATOR MODEL WHEN ELASTICALLY CONNECTED TO THE FRAME

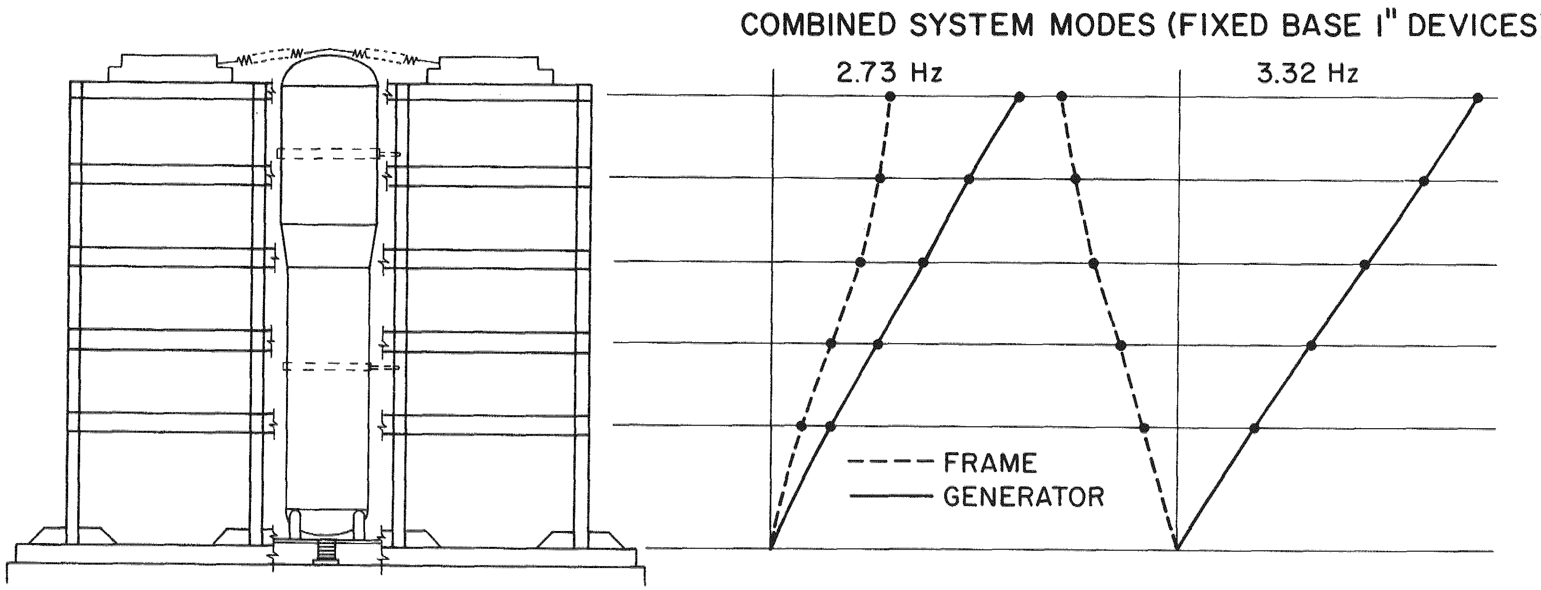

FIGURE 22 ESTIMATE OF MODE SHAPES FOR THE COMBINED SYSTEM

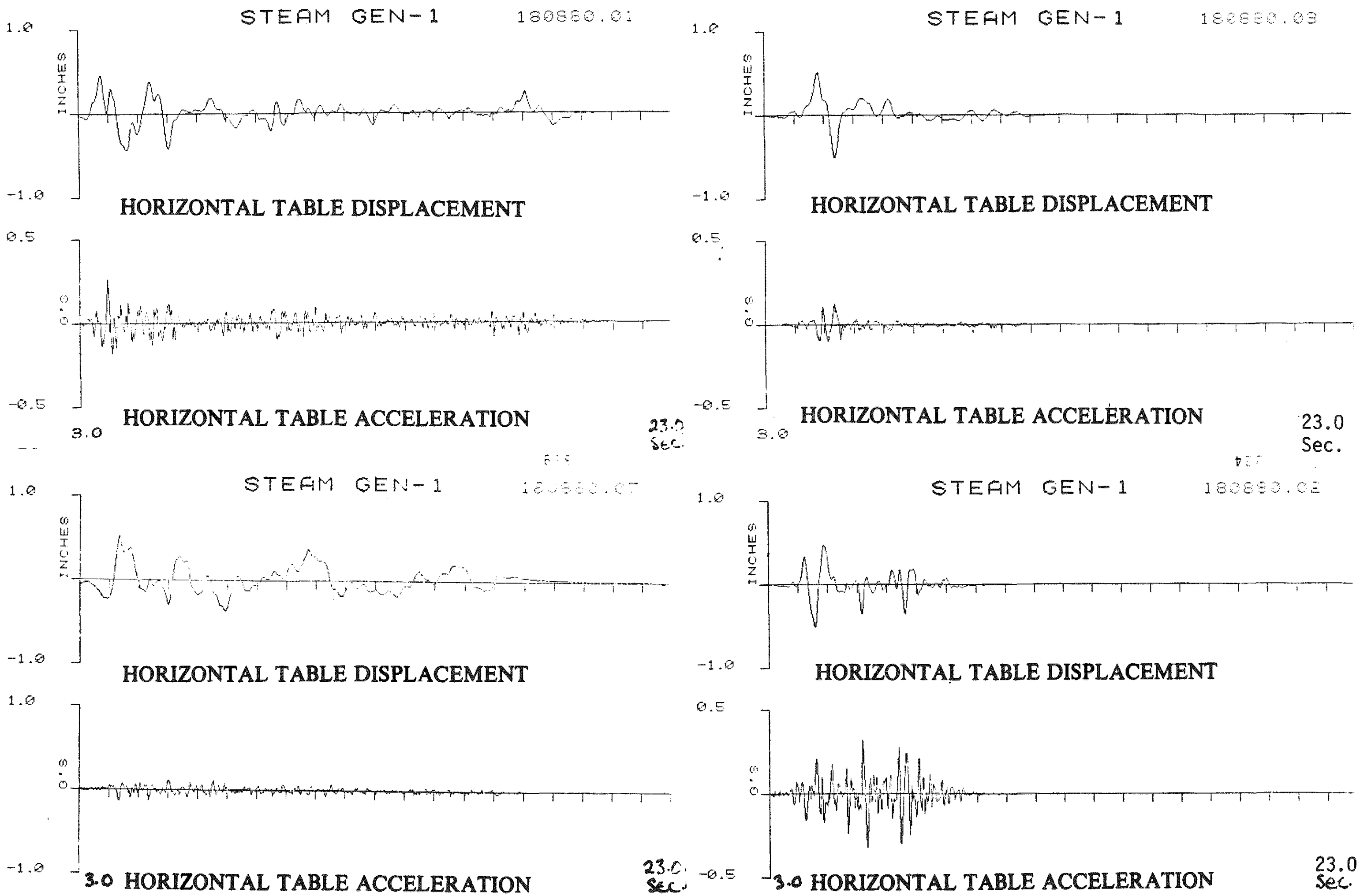

FIGURE 23 DISPLACEMENT AND ACCELERATION TIME HISTORIES FOR THE FOUR TIME-SCALED EARTHQUAKE RECORDS USED AS TABLE INPUT

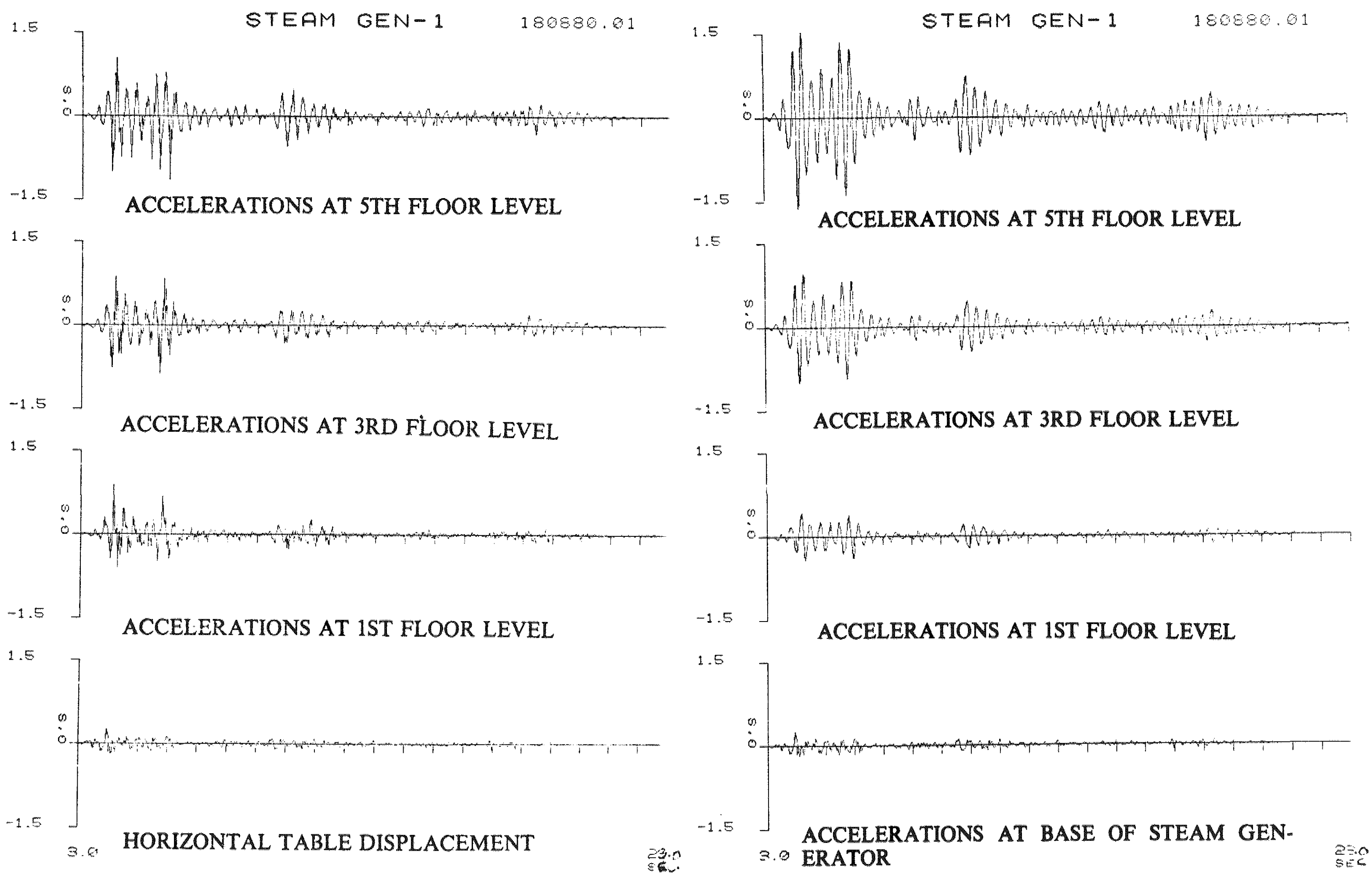

FIGURE 24 TIME-HISTORY PLOTS FOR THE COMBINED CONVENTIONAL SYSTEM

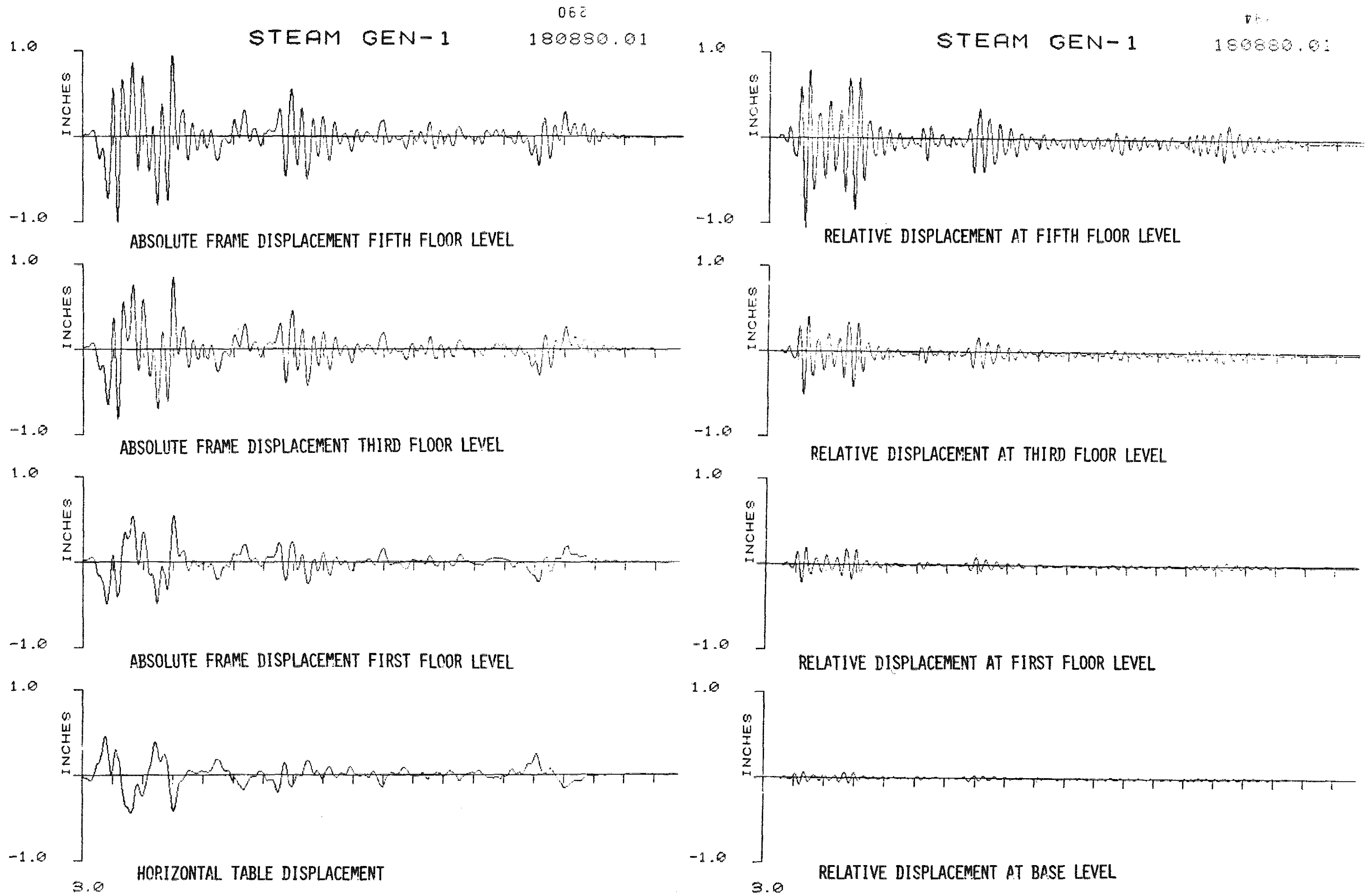

FIGURE 24 (cont'd) TIME-HISTORY PLOTS FOR THE COMBINED CONVENTIONAL SYSTEM

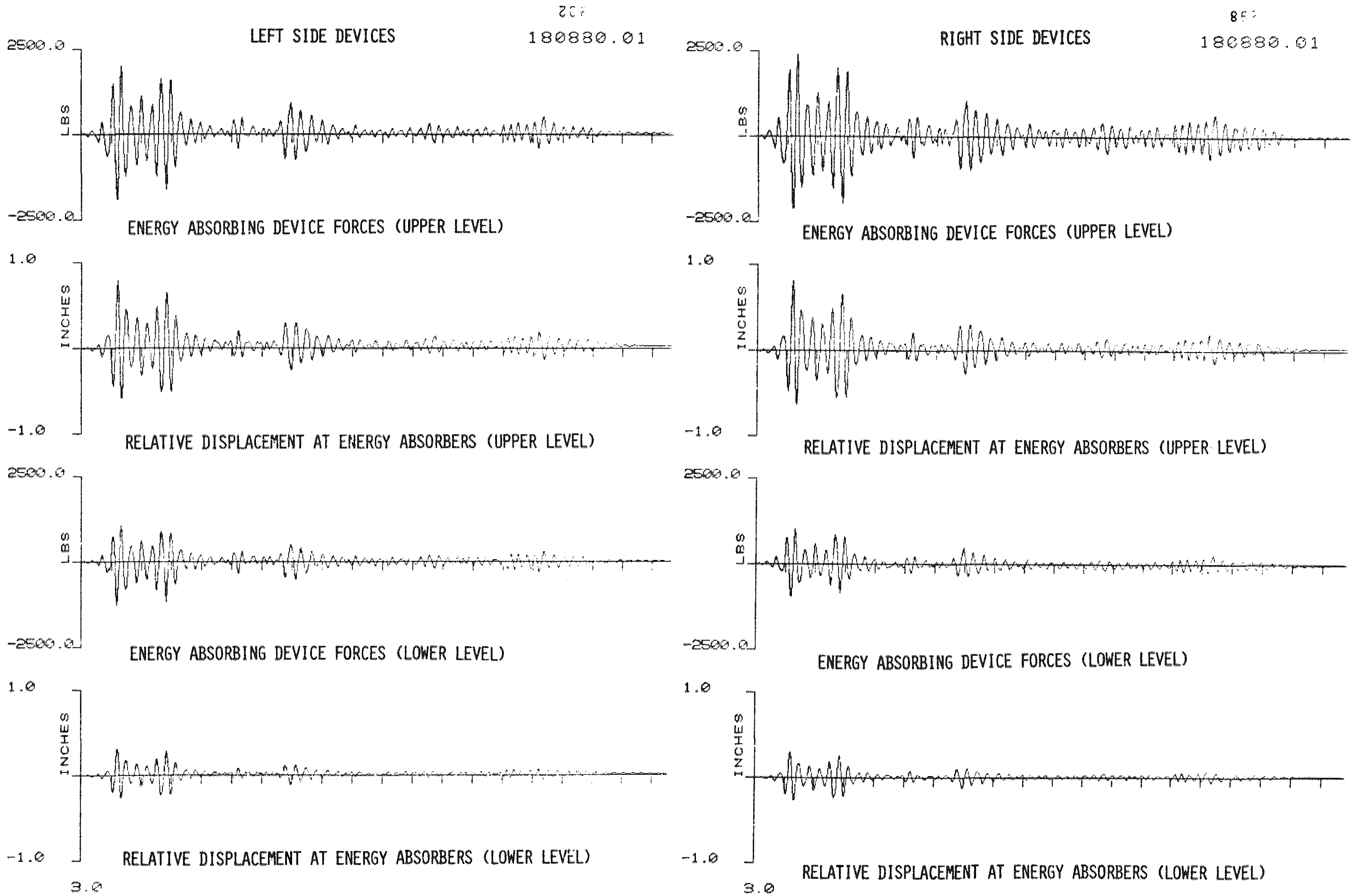

FIGURE 24 (cont'd) TIME-HISTORY PLOTS FOR THE COMBINED CONVENTIONAL SYSTEM

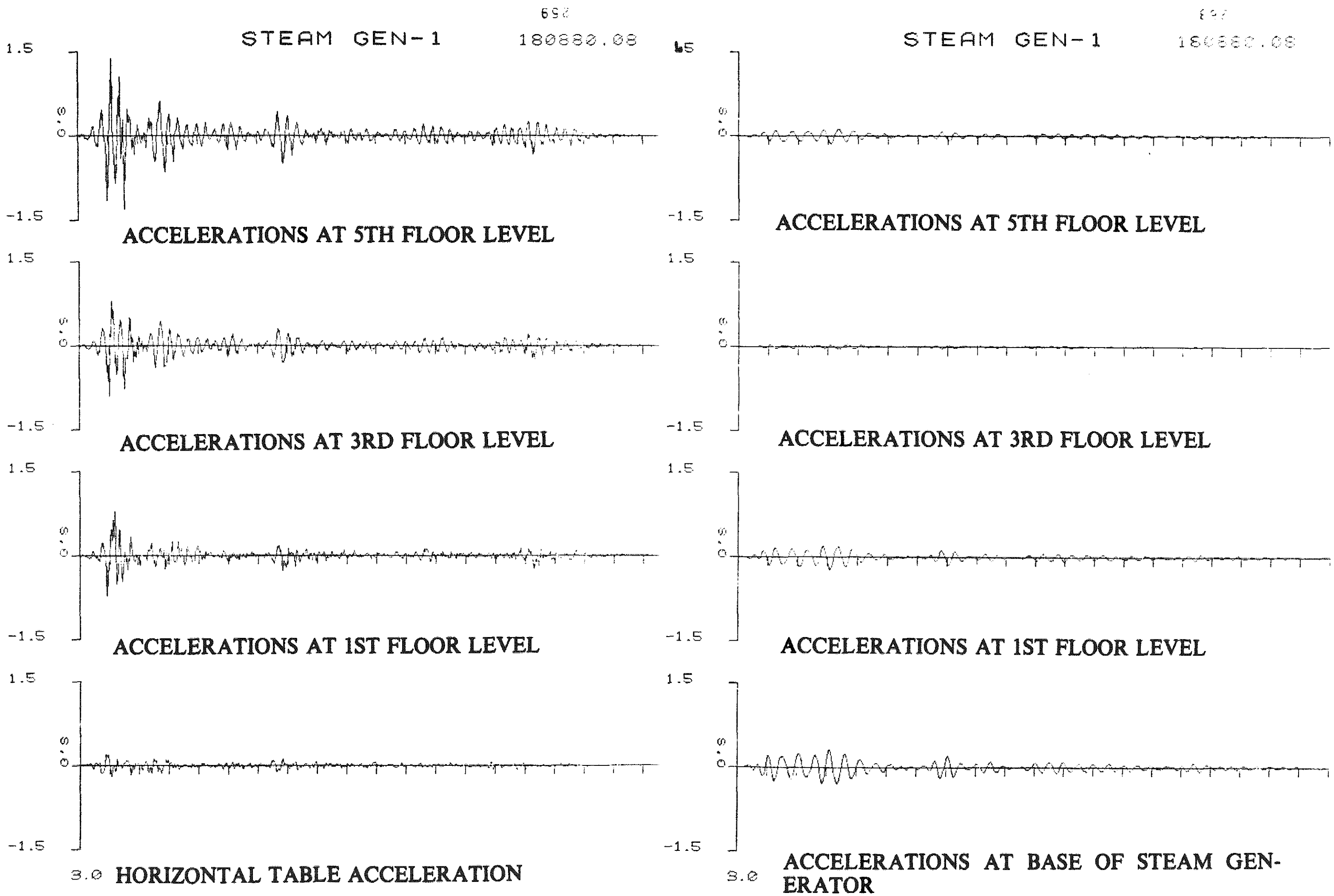

FIGURE 25 TIME-HISTORY PLOTS FOR THE INDEPENDENT ISOLATED CASE (STEAM GENERATOR MODEL ON RUBBER BEARING AND WITH NO ENERGY-ABSORBING DEVICES)

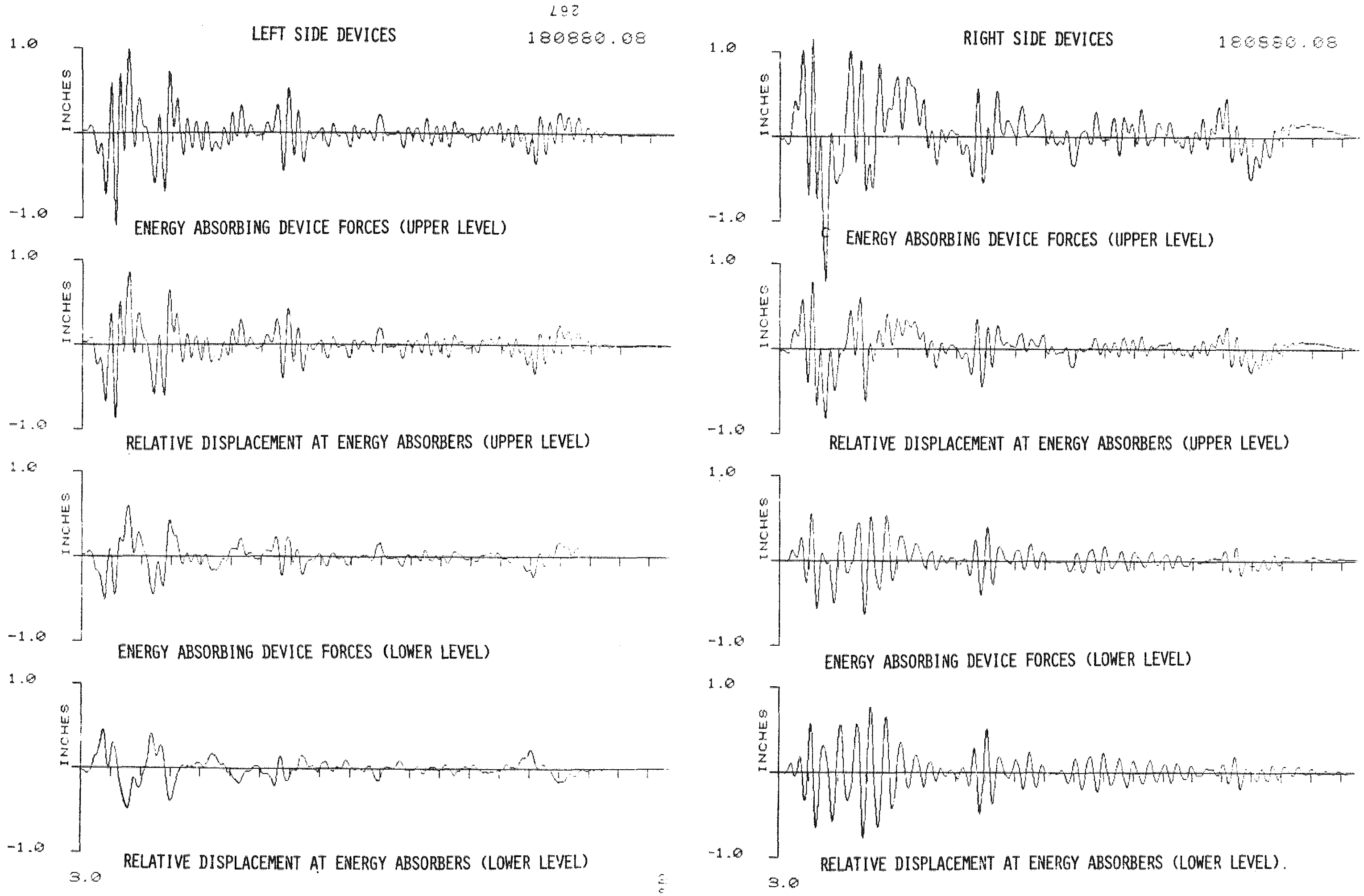

FIGURE 25 (cont'd) TIME-HISTORY PLOTS FOR THE INDEPENDENT ISOLATED CASE

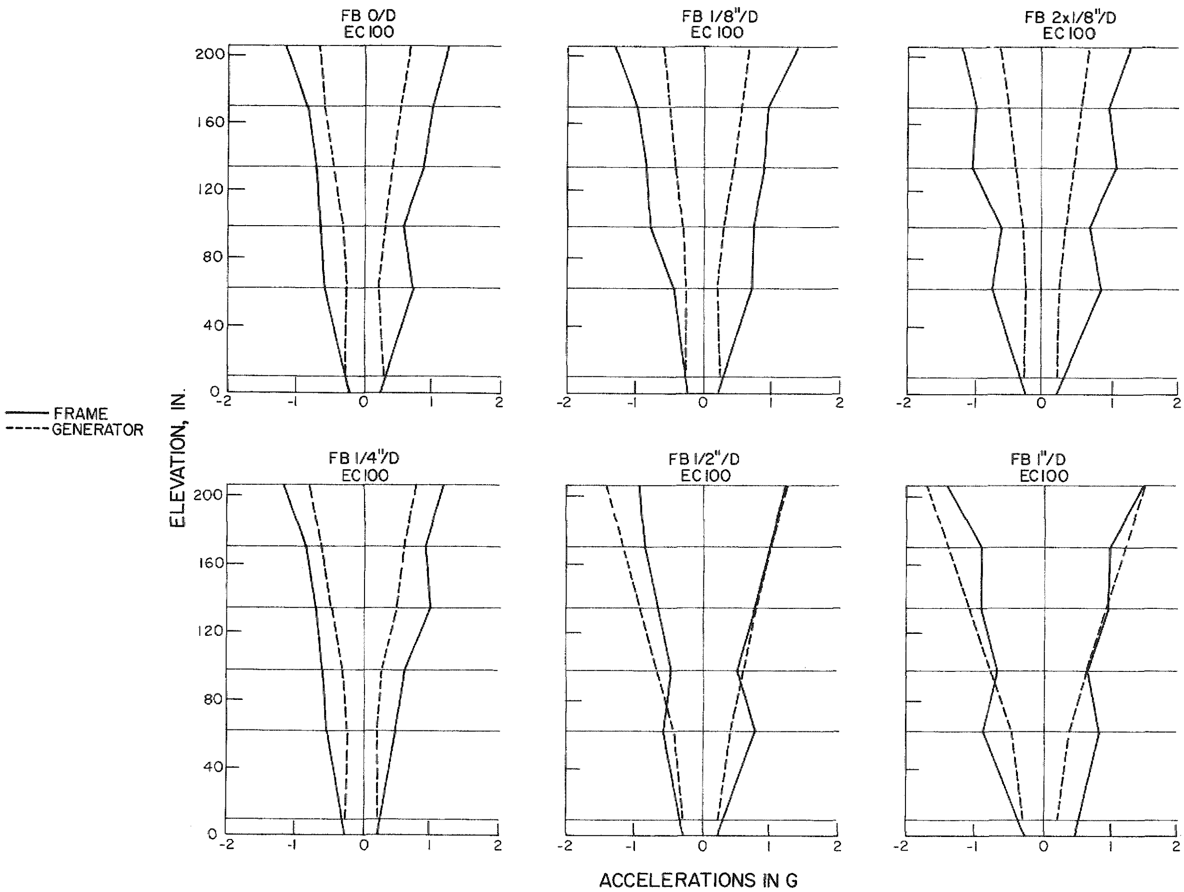

FIGURE 26 PEAK ACCELERATIONS IN THE FRAME AND THE STEAM GENERATOR MODEL FOR THE FIXED-BASE CONDITION

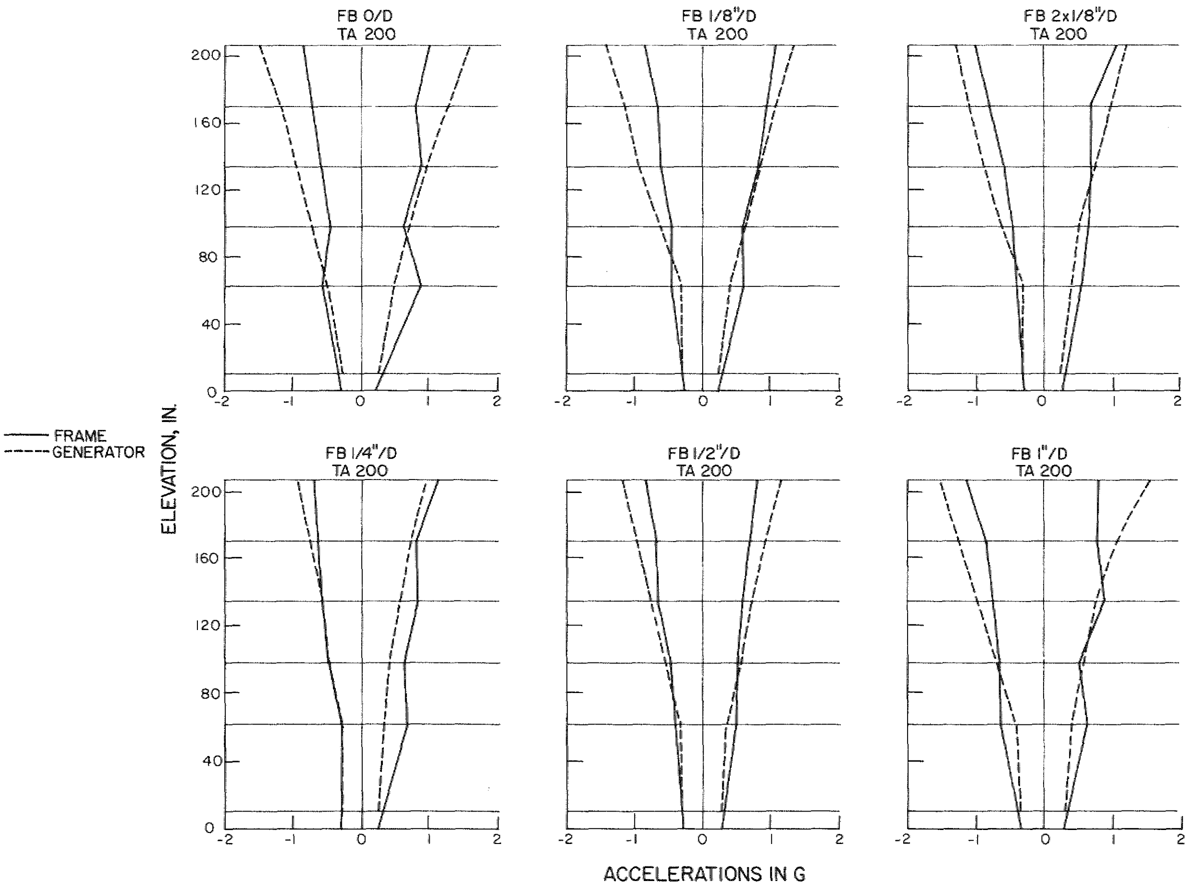

FIGURE 26 (cont'd) PEAK ACCELERATIONS IN THE FRAME AND THE STEAM GENERATOR MODEL FOR THE FIXED-BASE CONDITION

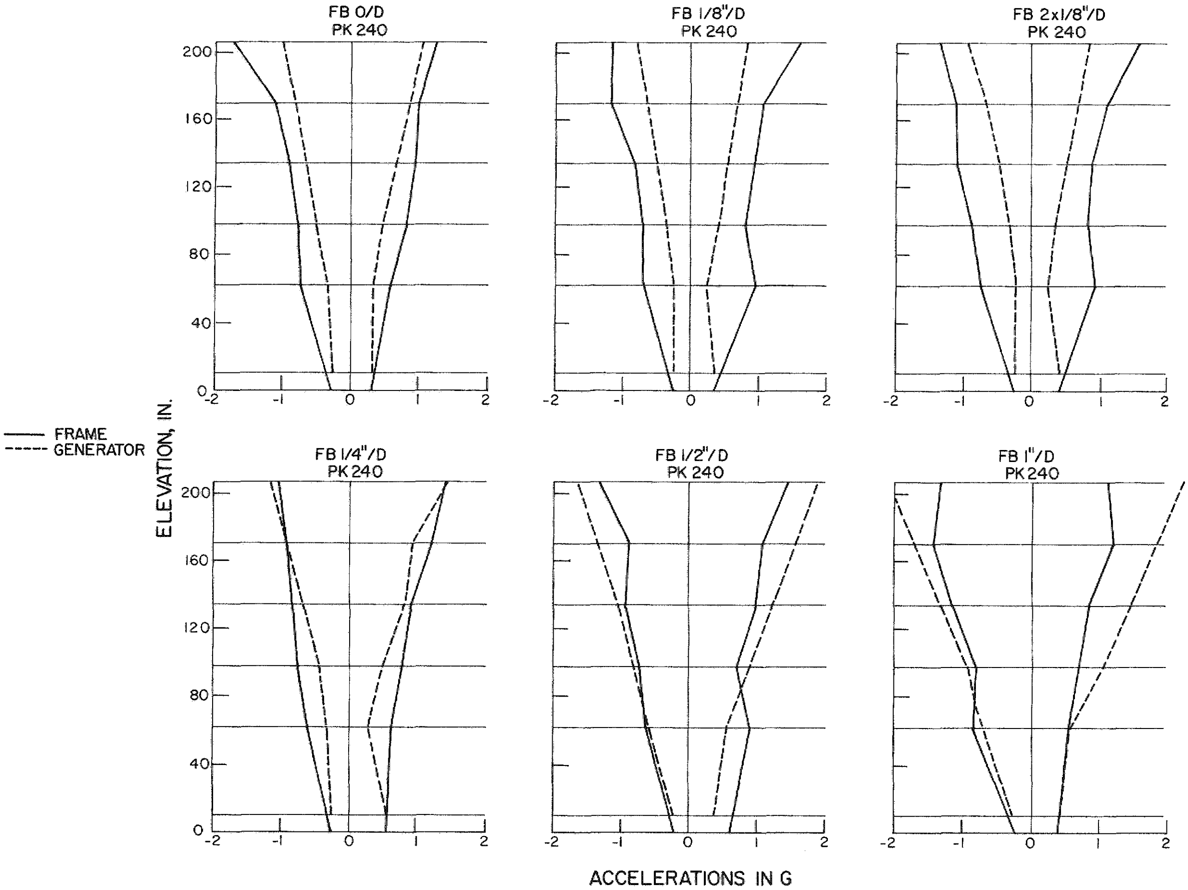

FIGURE 26 (cont'd) PEAK ACCELERATIONS IN THE FRAME AND THE STEAM GENERATOR MODEL FOR THE FIXED-BASE CONDITION

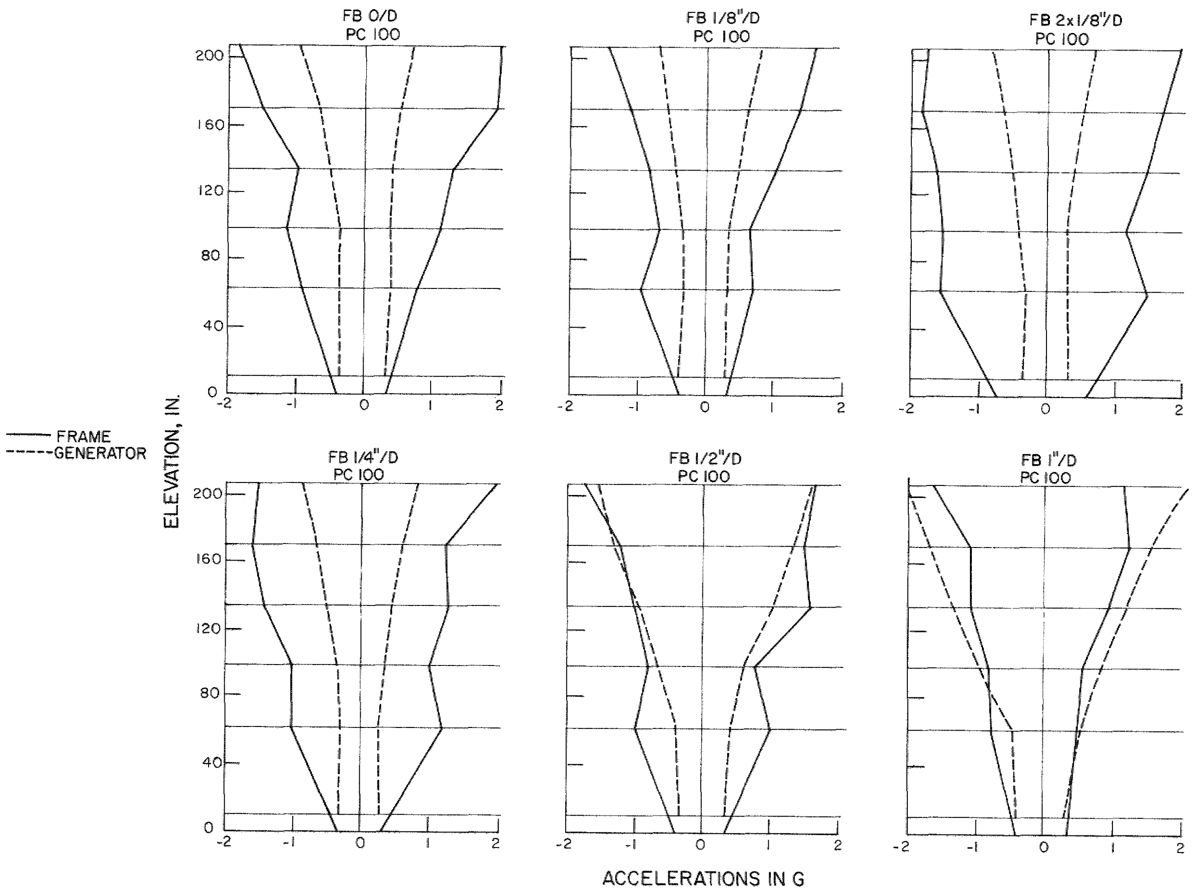

FIGURE 26 (cont'd) PEAK ACCELERATIONS IN THE FRAME AND THE STEAM GENERATOR MODEL FOR THE FIXED-BASE CONDITION

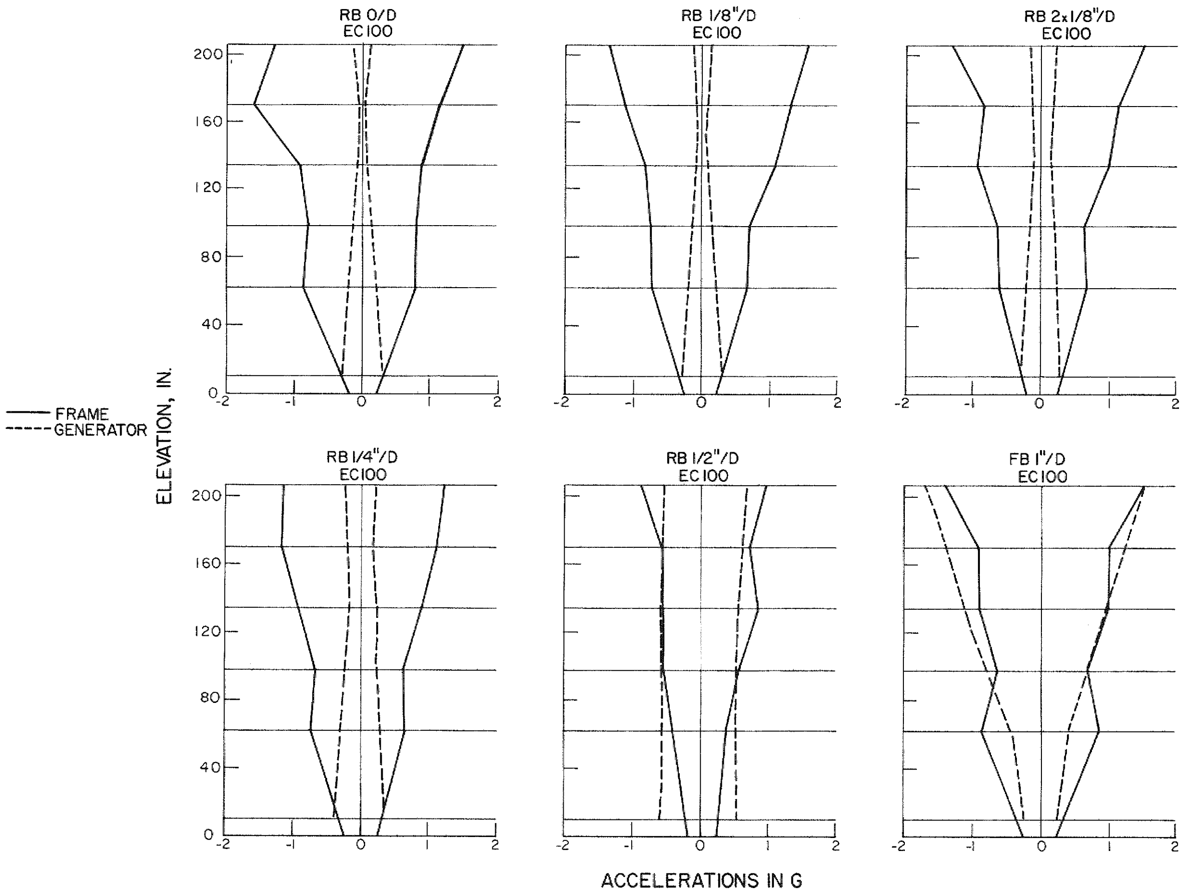

FIGURE 27 PEAK ACCELERATIONS IN THE STEAM GENERATOR IN THE RUBBER-BASED CONDITION

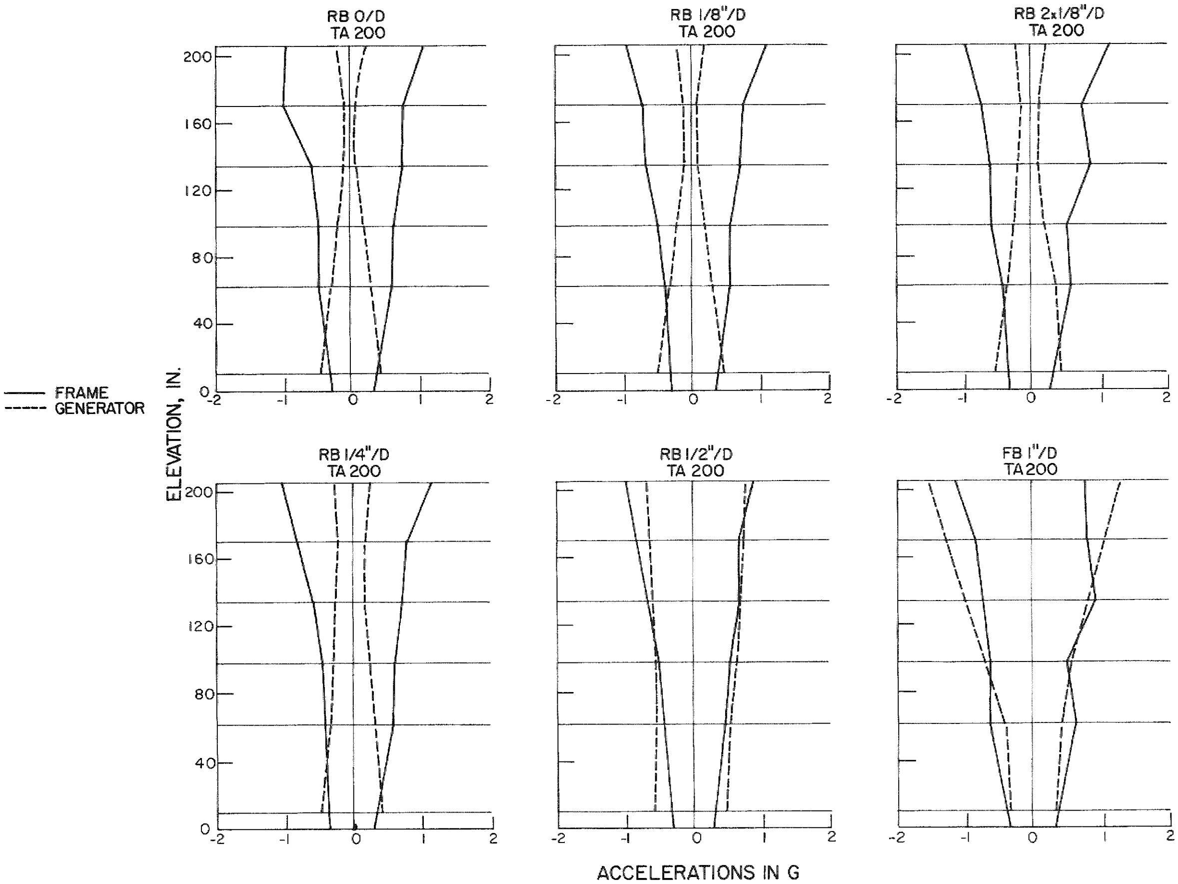

FIGURE 27 (cont'd) PEAK ACCELERATIONS IN THE STEAM GENERATOR MODEL FOR THE RUBBER-BASED CONDITION

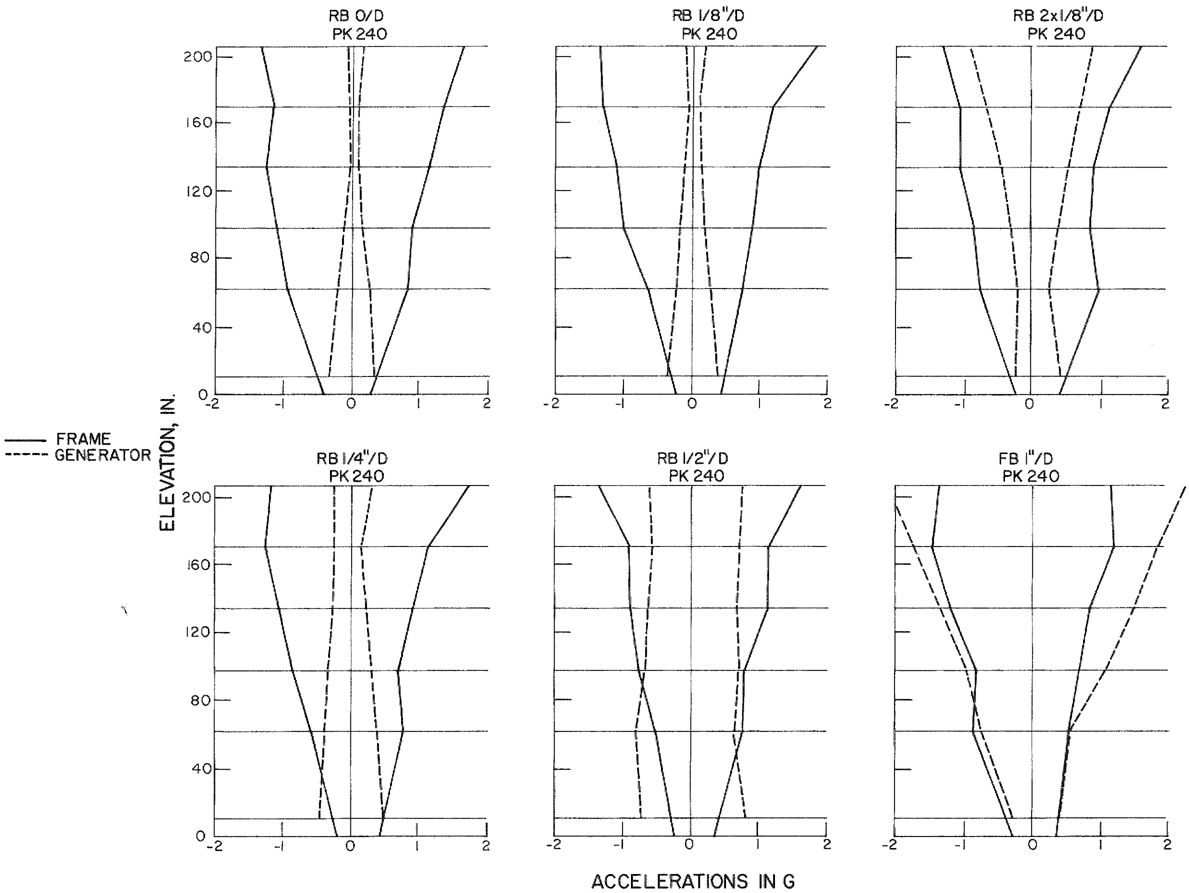

FIGURE 27 (cont'd) PEAK ACCELERATIONS IN THE STEAM GENERATOR MODEL FOR THE RUBBER-BASED CONDITION

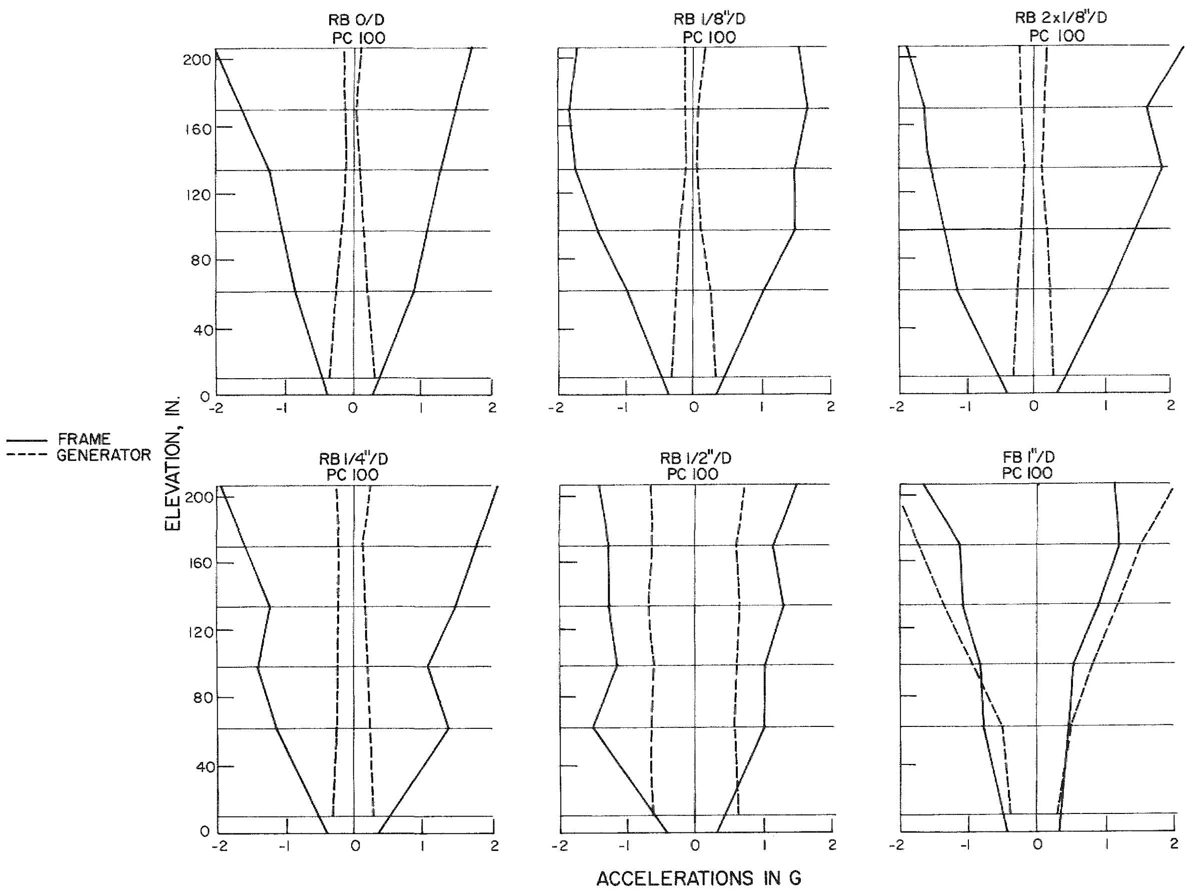

FIGURE 27 (cont'd) PEAK ACCELERATIONS IN THE STEAM GENERATOR MODEL FOR THE RUBBER-BASED CONDITION

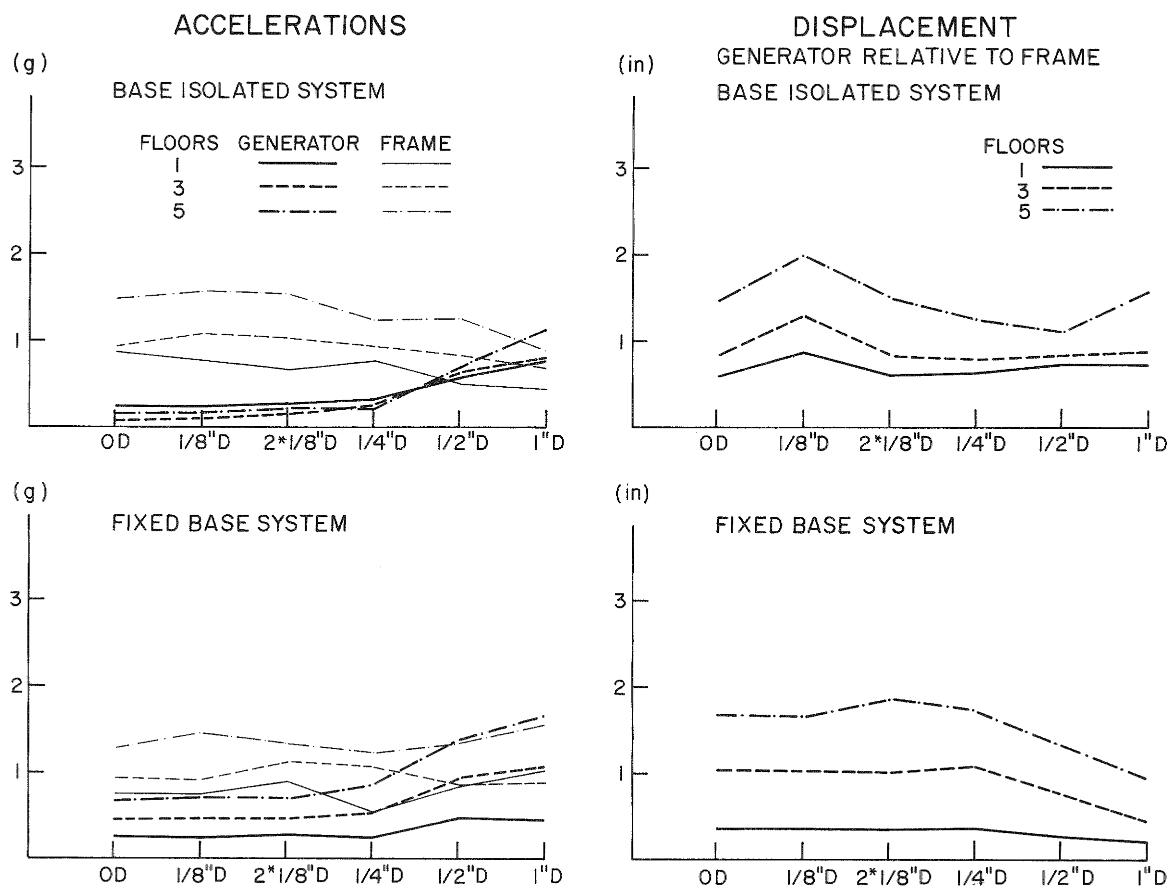

FIGURE 28 PEAK ACCELERATIONS AND MAXIMUM RELATIVE DISPLACEMENTS AS FUNCTIONS OF THE DIFFERENT ENERGY-ABSORBING DEVICES

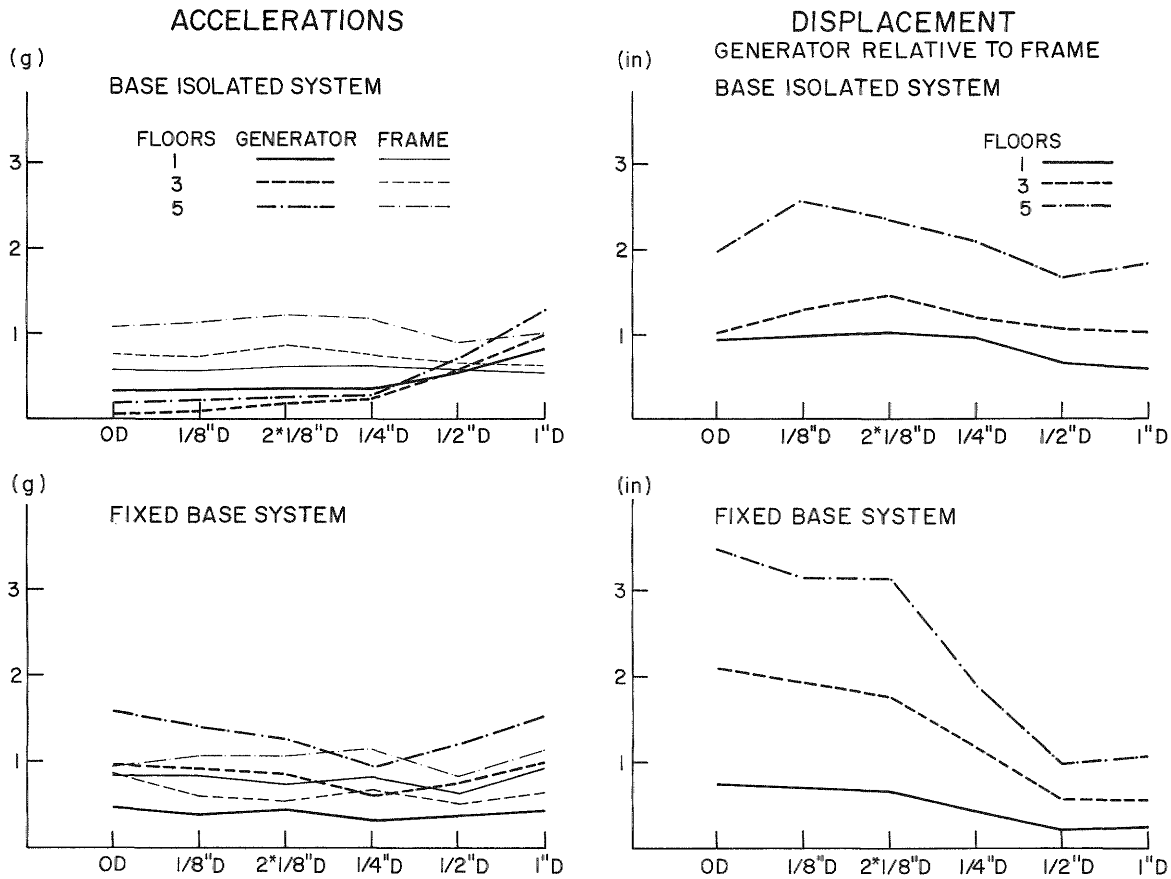

FIGURE 28 (cont'd) PEAK ACCELERATIONS AND MAXIMUM RELATIVE DISPLACEMENTS AS FUNCTIONS OF THE DIFFERENT ENERGY-ABSORBING DEVICES

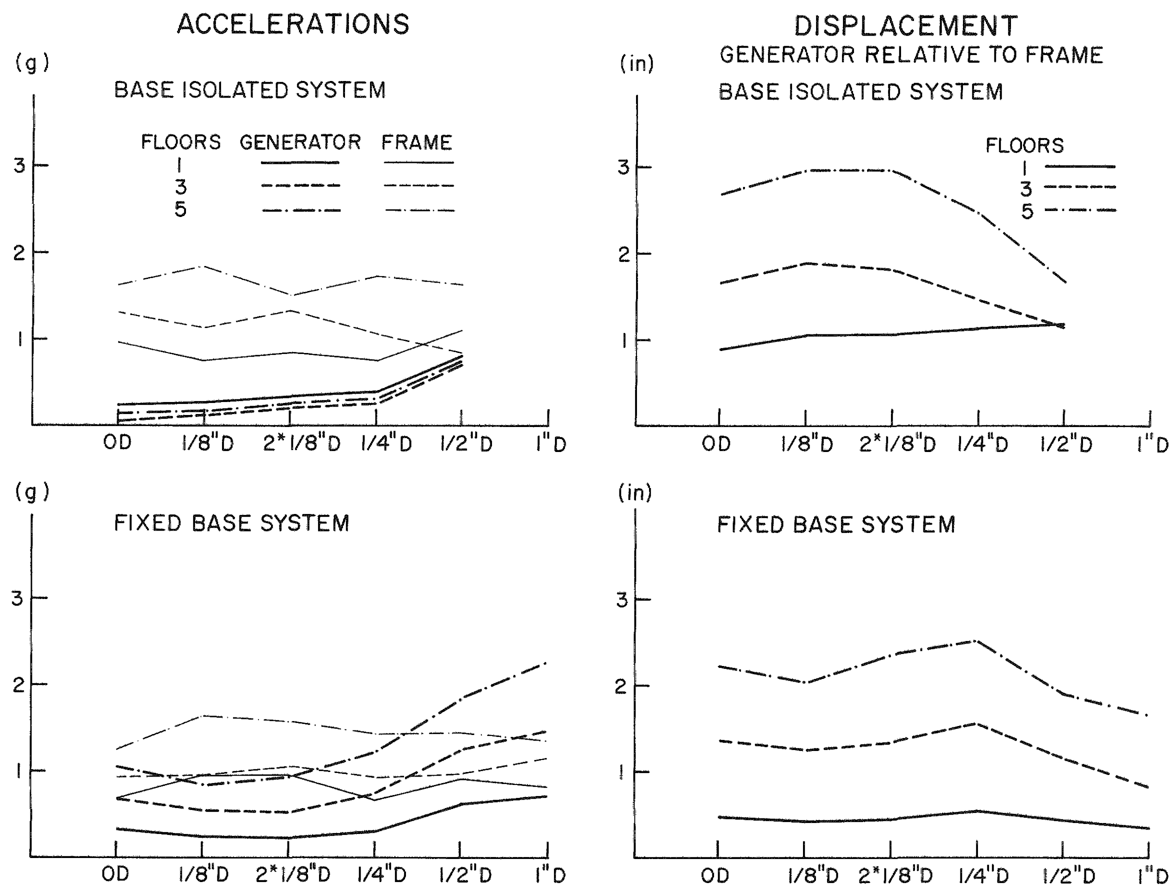

FIGURE 28 (cont'd) PEAK ACCELERATIONS AND MAXIMUM RELATIVE DISPLACEMENTS AS FUNCTIONS OF THE DIFFERENT ENERGY-ABSORBING DEVICES

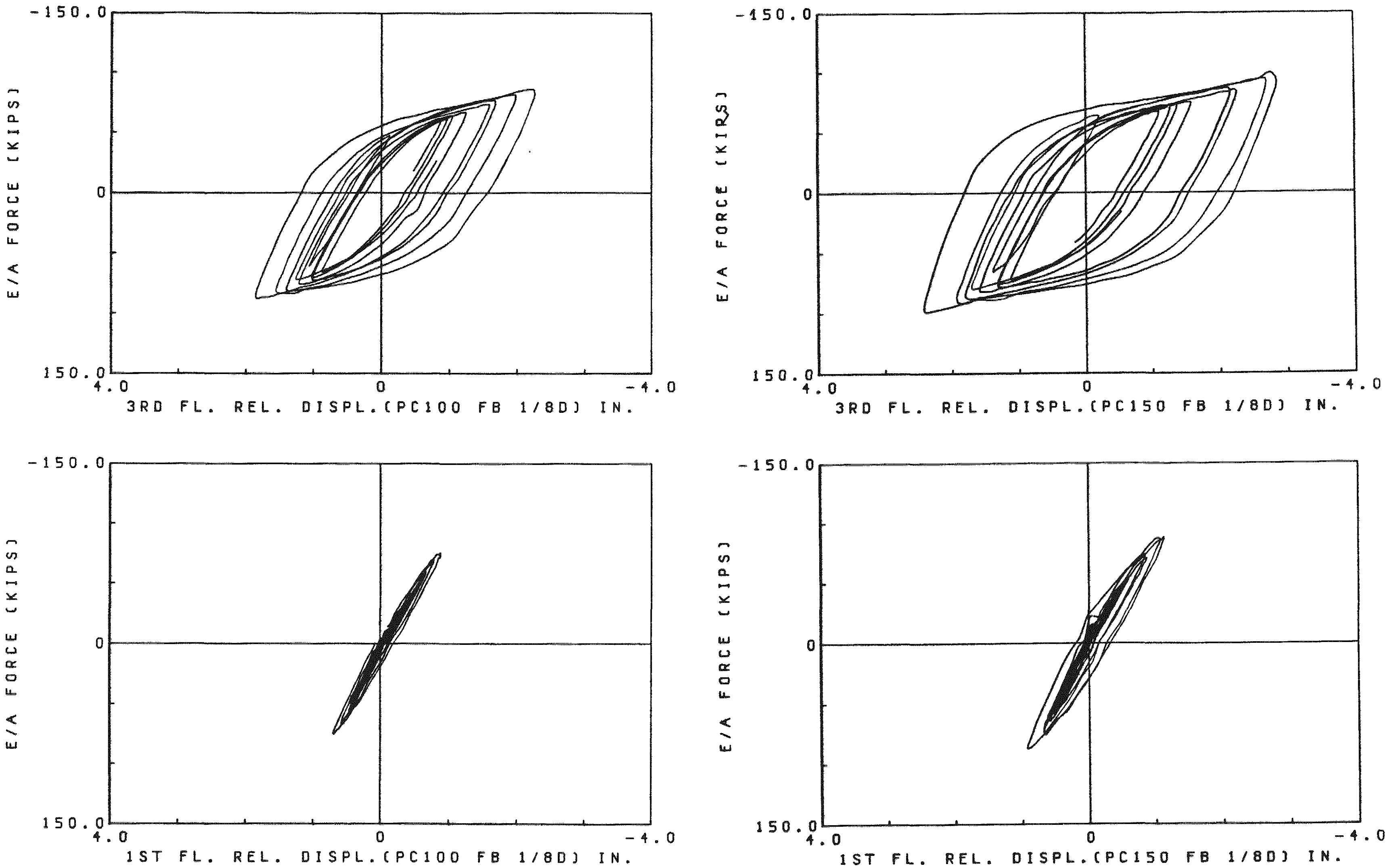

FIGURE 29   DYNAMIC HYSTERESIS LOOPS FOR THE FIXED-BASE CONDITION

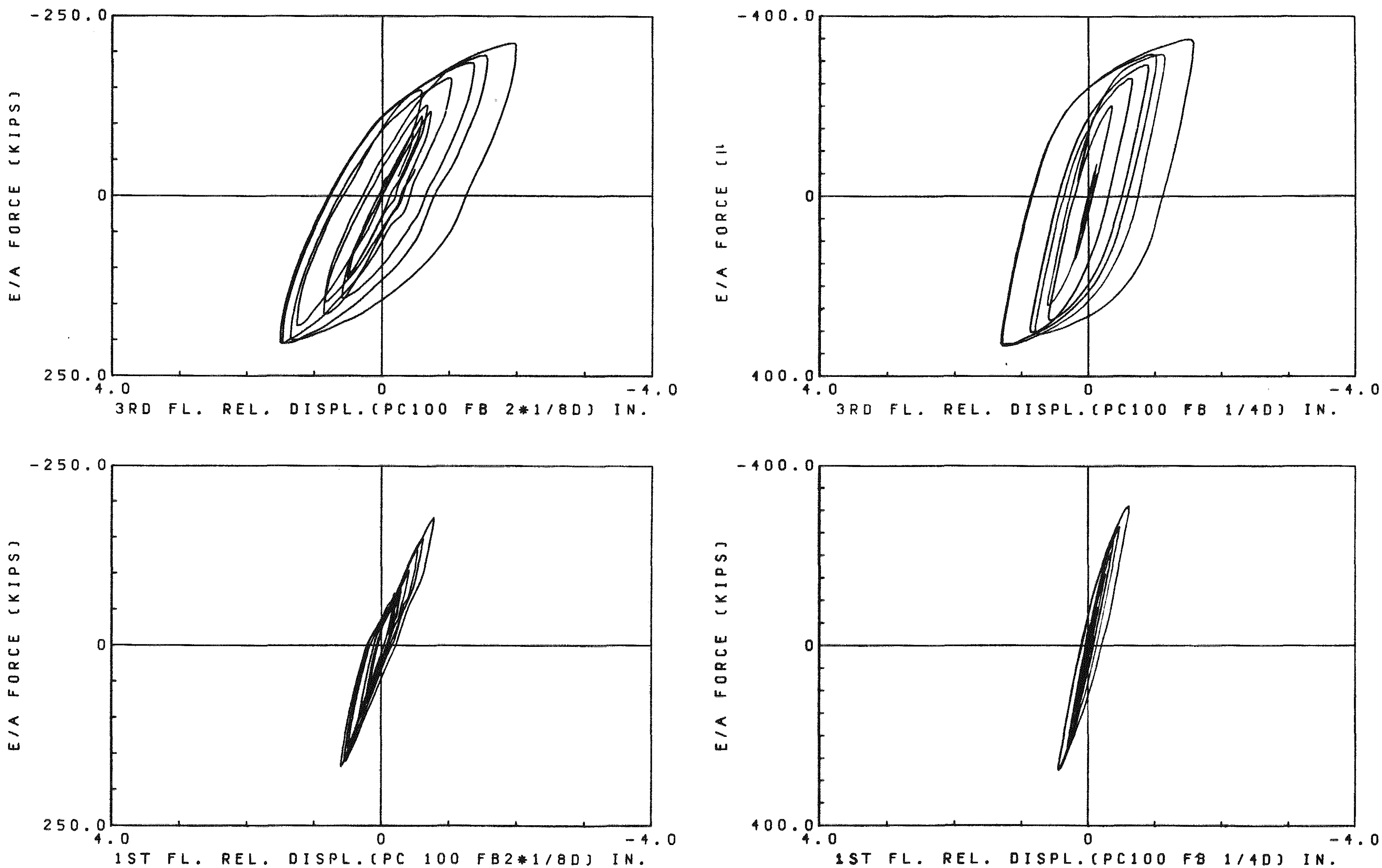

FIGURE 29 (cont'd) DYNAMIC HYSTERESIS LOOPS FOR THE FIXED-BASE CONDITION

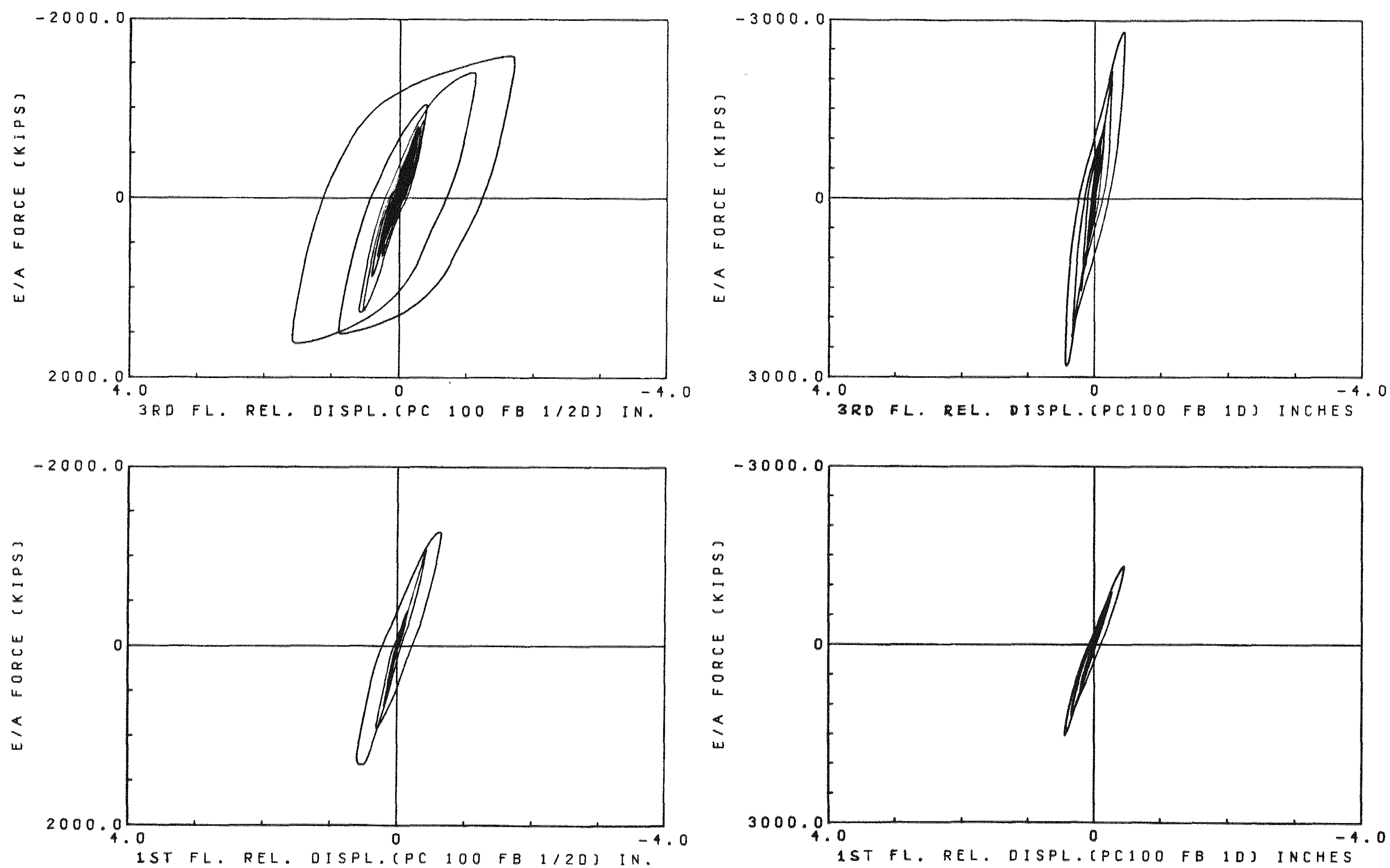

FIGURE 29 (cont'd) DYNAMIC HYSTERESIS LOOPS FOR THE FIXED-BASE CONDITION

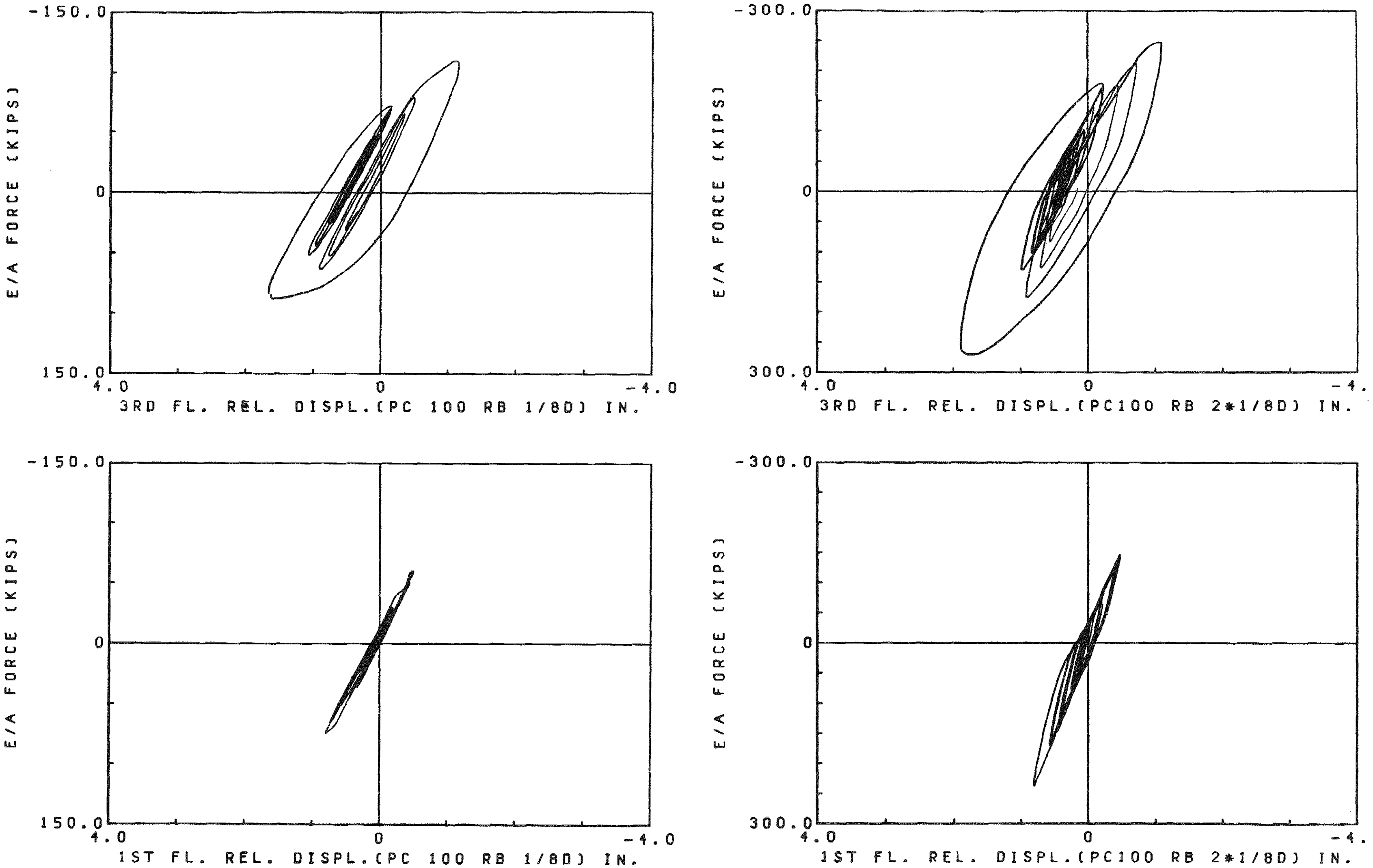

FIGURE 30 DYNAMIC HYSTERESIS LOOPS FOR THE ISOLATED CONDITION

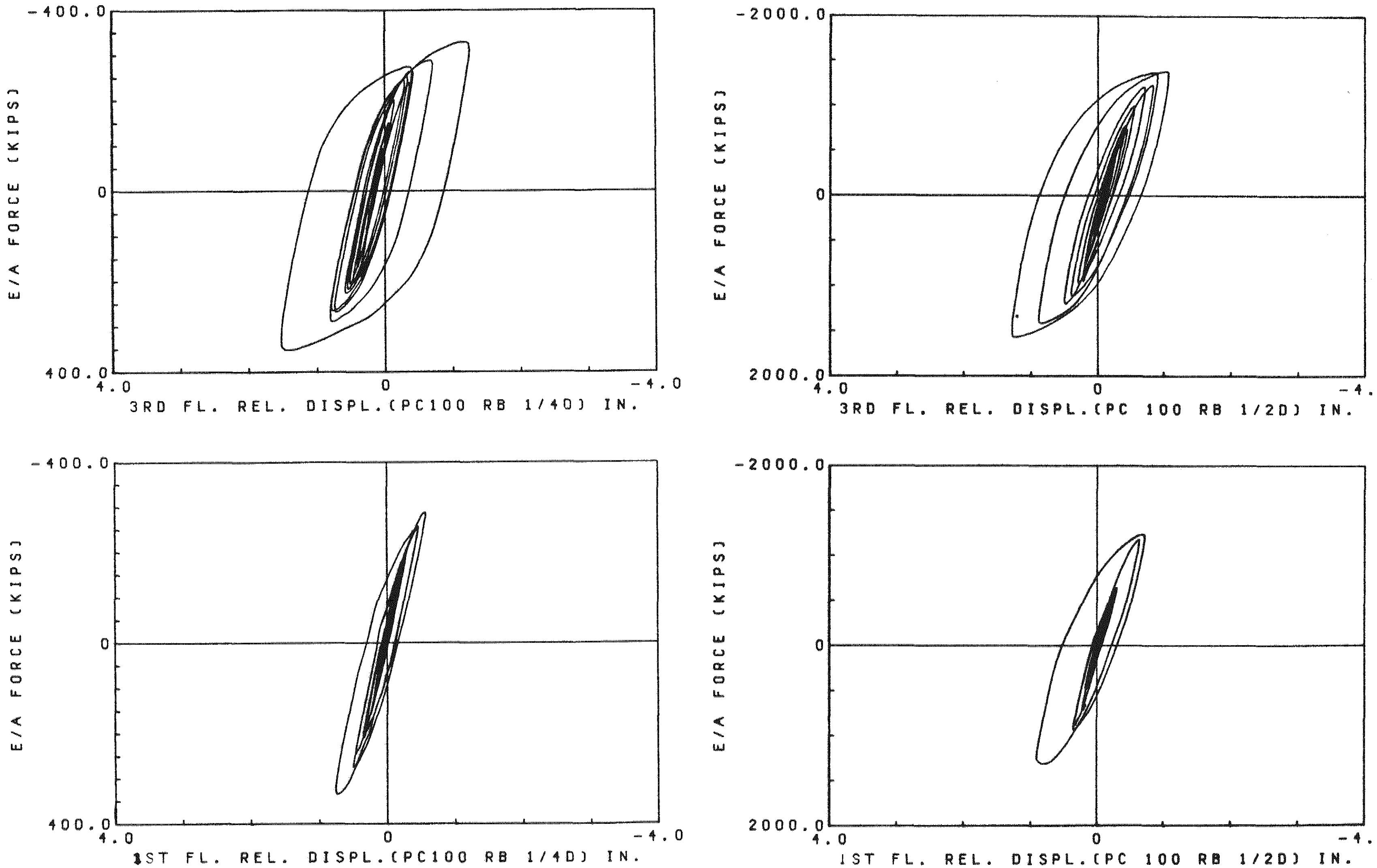

FIGURE 30 (cont'd) DYNAMIC HYSTERESIS LOOPS FOR THE ISOLATED CONDITION