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EXPERIMENTAL TESTING OF A FRICTION DAMPED ASEISMIC BASE ISOLATION SYSTEM WITH FAIL-SAFE CHARACTERISTICS

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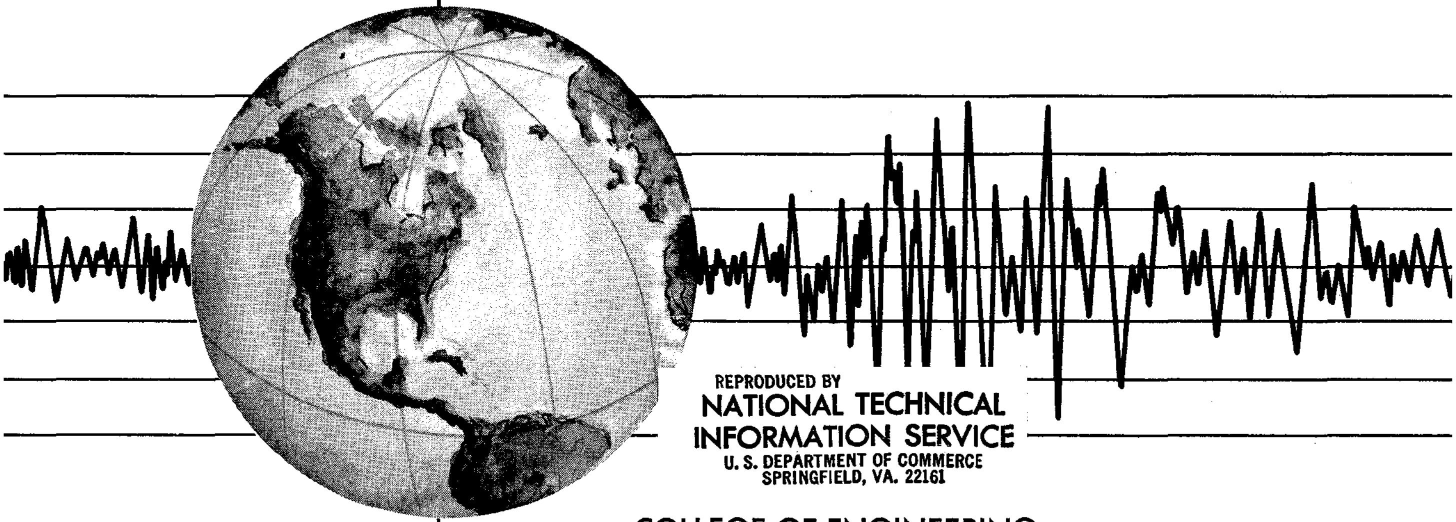

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EXPERIMENTAL TESTING OF A FRICTION DAMPED ASEISMIC BASE ISOLATION SYSTEM WITH FAIL-SAFE CHARACTERISTICS

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Abstract

An experimental study of a Coulomb friction damped aseismic base isolation system with fail-safe characteristics is described in this report. The base isolation system utilized commercially made natural rubber bearings and a skid system which comes into operation at preset levels of relative horizontal displacement between the structure and the foundations. The fail-safe skid provides hysteretic damping and prevents failure of the isolation system in the event of displacements larger than those assumed in the original design. The isolation system can be designed for an earthquake which can be reasonably expected within the lifetime of the structure; in the event of an earthquake of unanticipated intensity the fail-safe system will prevent collapse of the structure.

The testing of the system involved an 80,000 lb model, approximately 1/3 scale to a real structure mounted on the 20' x 20' shaking table at EERC and subject to a variety of earthquake inputs. The results show that the hysteretic effect of the fail-safe system does not greatly increase the accelerations experienced by the structure but considerably reduces the relative displacements at the isolation bearings. The action of the fail-safe system was tested by using an earthquake input that produced a resonant response in the isolated mode of the model. The stability limit of the isolation system was exceeded and the bearings failed but complete failure of the isolation system and thus collapse of the model was prevented by the fail-safe system. The implementation of the system in full scale structures poses no technical or construction problems.

1. Introduction

Base isolation is an approach to aseismic structural design in which a building is uncoupled from the damaging horizontal components of an earthquake by a mechanism of some type which prevents or reduces the transmission of horizontal acceleration into the structure.

Many unimplemented base isolation systems have been proposed over the past one hundred years (see [1] for review) but the concept has become a practical possibility with the recent development of multilayer elastomeric bearings. Bearings for use in an aseismic base isolation system are a development of bridge bearings [1] and of bearings used to isolate structures from ground-borne acoustic vibration, as for example subway noise [2]. Such bearings have excellent reliability and longevity and are resistant to environmental damage, including oil and fire [3].

Over the past few years we have carried out an extensive series of experiments on this concept using the shaking table at the EERC. These tests utilized a three-story, single-bay frame and handmade isolation bearings of natural rubber. The results of these tests have been published [see refs. 4,5,6,7]. These results have established the effectiveness of the approach to aseismic design and have shown that substantial reductions in the peak acceleration are experienced by a building on an isolation system over one on a conventional foundation.

The concept of base isolation is a natural one based on accepted physical principles. However, its acceptance by the structural engineering profession has been slow and a possible reason is the following. It is an accepted premise of structural design that a building should respond with minimal damage (essentially elastically) to a moderate earthquake of an intensity reasonably anticipated within the lifetime of the structure. For an earthquake of unanticipated intensity it is acceptable that the structure can suffer significant damage but must not collapse, thus ensuring the safe evacuation of occupants. In the case of an isolation system using elastomeric bearings, it is possible that the bearings might fail in an earthquake of unanticipated intensity and bring about the collapse of the building. One of the objectives of the present research is to investigate the behavior of a fail-safe system which will prevent failure of the system in an earthquake of an intensity much larger than that for which they were designed. The operation of the fail-safe system, it will be shown, can introduce higher accelerations into the structure and cause some damage. However under this design philosophy such damage would be acceptable and total collapse of the building would be avoided.

Another objective of this test series was to test a system of elastomeric bearings made by a commercial rubber company using standard molds. The bearings used in the previous tests [4,5,6,7] were handmade bearings and it was felt important to verify the efficacy of bearings made by conventional methods. These bearings were considerably stiffer than the handmade bearings so that a larger model was needed. The experimental work described here involved the use of a new five-story, three-bay steel frame with a total weight of approximately 80,000 lbs including the base level. This frame is a more realistic model of a conventional structure than the model used previously [4,5,6,7]. The model represents a conventional structural system at a scale of about 1/3.

The operation of the fail-safe system is two-fold. It is designed to introduce a steadily increasing amount of Coulomb friction into the isolation system; in this way the response is reduced by the damping so induced. Under earthquake action which slightly exceeds the intensity for which the system has been designed this added damping will be enough to limit the response of the isolation system to levels of relative horizontal displacement within the stability limits of the elastomeric bearings. Under earthquake action beyond this level at which the stability limit of the bearings could be exceeded and the bearings collapse the structure is carried on the fail-safe system. At this point the isolation system mechanism changes to sliding friction; the accelerations transmitted to the building will naturally be higher than those if the elastomeric bearings were acting alone but it is the premise of the design philosophy that damage to the structure would be acceptable if collapse of the building is prevented.

In this report we describe a successful test of the fail-safe system in which the model was loaded in such a way to produce failure of the bearings and thus bring into action the fail-safe system.

2. Test Facilities

The experiments reported here were carried out at the Earthquake Simulator Laboratory of the EERC at Richmond Field Station of the University of California, Berkeley. The main dynamic test facility is a 20' x 20' shaking table with its associated control equipment, described by Rea and Penzien [8].

The shaking table is a 20' x 20' x 1', prestressed concrete slab, driven independently in the vertical direction and in one horizontal direction by servo-controlled actuators. The 100^k dead weight of the table, plus the weight of a model, is supported by differential air pressure during operation, thus relieving the vertical actuators 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 table motion with no model are given in ref. 8. 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 data 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 9 track magnetic tape drive for permanent storage.

3. The Test Model

i) Frame

The experimental model used is shown in Fig. 1. It is a five-story frame mounted on two heavy (16WF) base floor girders that are supported by four sets of rubber bearings resting on load cells. The load cells are anchored onto the shaking table with high-tension stress rods. The dead load is provided by concrete blocks tied down to the frame at different floor levels as shown in Fig. 1. The weight of the dead load adds up to 72 kips, which gives an approximate total weight of 80 kips for the whole structure. Thus a compressive force of approximately 20 kips is produced in each of the bearings. Centered underneath each of the two base floor girders are the two skid systems (described later) resting on two load cells each. Those load cells are also connected to the table with high-tension stress rods. The clearance between the skids and the base floor girders was adjusted by inserting shims between the skids and the load cells until the desired clearance was achieved.

The dead load provided by the concrete blocks produces stress levels comparable to those in a full scale structural frame and the geometrical scale factor of the model is roughly 1/3. The corresponding time scale factor will be $\sqrt{3}$.

In addition to the different isolated conditions produced by varying the clearance of skid beam system, a fixed condition was developed to enable isolated system results to be compared with those for the non-isolated system. The fixed condition was achieved by attaching straps between base floor girders and base plates under the load cells at each bearing as shown in Fig. 2. In addition the skid system was brought into contact with the floor girders and they were clamped together.
The results indicate that this process was effective in eliminating relative displacement between frame and shaking table (see Fig. 10d).

ii) Fail-Safe Skid System

Under each base floor girder in the space between the bearings a 8" x 8" WF beam 6' long was position on load cells. A small adjustable clearance was left between this beam and the base floor girder above. This is referred to in the report as fail-safe skid system and it serves a dual purpose.

The first is to act as a "Fail-Safe System." The bearings can be designed for a specific maximum relative displacement based on a specific design earthquake. In the event of unexpectedly large relative displacements which could cause the bearings to fail the system would not collapse but be "caught" on the Skid System. When the elastomeric bearings are under high load due to the weight of the supported structure and are deflected laterally due to shear strain in excess of 100%, the coupling of the vertical load and the horizontal displacement produces a vertical shortening of the bearings in addition to that produced by the vertical load. This additional vertical displacement is quadratic in the horizontal displacement and although small, e.g. less than 1/5 inch for a four inch lateral displacement of the eight-inch high bearing used in the experiments, it can be exploited to activate a fail-safe system which will come into play only when the design earthquake intensity is exceeded. (In Fig. 3 the horizontal force displacement relationship for a bearing is shown; also included is the vertical displacement associated with the horizontal displacement.) This system when activated will introduce high damping and controlled resisting forces and by taking and increasing share of the vertical load prevent the instability of the rubber bearings. Thus the system will, in effect, act as a fail-safe system for the base isolation system.

Its second purpose is to function as a Coulomb friction damper. As noted above, increasing relative displacements (lateral deformation of the bearings) are associated with increasing vertical deformation. After the base floor girders and the skids contact at a certain value of relative horizontal displacement, a shearing force in the skids is developed and vertical load is transferred from the bearings to the skids. This has the effect of limiting the maximum displacement. The shearing force in the skids is due to friction, and can be assumed to be proportional to the normal pressure as in Coulomb friction. The Coulomb fricition force introduces hysteretic damping into the system in the form of a damping force which is proportional to the displacement but in phase with the velocity.

Both these functions of the fail-safe skid system were tested and investigated during this test series and the results are reported in this paper. For a fixed clearance between the skid system and the base floor girders the vertical deformation associated with lateral displacement will tend to close the gap and eventually bring the two sets of beams (skid system and base floor girders) into contact. The value of the relative displacement at contact can be changed by adjusting the clearance between the base floor girders and the supporting system at zero relative horizontal displacement.

Results will presented for the following clearances between the skids and the base girders: HC - HIGH CLEARANCE which means contact after approximately 2" displacement; MC - MEDIUM CLEARANCE contact after approximately 1" relative displacement; LC - LOW CLEARANCE contact at 0" relative displacement.

iii) Bearings

The bearings were manufactured for the test series by the Andre Rubber Company Ltd. They are of natural rubber reinforced by steel plates and were made in modules incorporating two 1/4" thick layers of rubber and three 1/8" steel plates. A complete bearing incorporated 10 such modules. The modules are epoxied together into complete units but the epoxy is not used to transmit the shear forces between layers. Instead steel disks 1/4" thick are keyed into circular holes in the 1/8" steel plates on the top of one module and on the bottom of the one above. These transmit shear forces between the modules. The bearings are keyed to the load cells at the bottom and to the steel frame at the top by the same disks. A typical bearing as installed is shown in Fig. 4.

Prior to the dynamic testing the bearings were statically tested in a specially designed press in which two were loaded to a specified vertical force and then horizontally deflected at the mid-line as shown in Fig. 5. These tests were done to verify the horizontal stiffness of the bearings under vertical load and to determine the vertical displacement consequent on horizontal displacement. It is typical of such elastomeric bearings that the horizontal stiffness decreases with increase of vertical load. For the bearings used, the loading curves for two bearings at various vertical loads are shown in Fig. 6 (the horizontal and vertical responses of two bearings under 20^k vertical load are shown in Fig. 3). At a vertical load of 20^k the horizontal stiffness of a single bearing was estimated to be 720 lbs/inch which gives a horizontal natural frequency of 0.6 Hz for the 80,000 lb structure.

iv) Instrumentation

The instrumentation for the table is permanently incorporated and records average vertical and horizontal table displacement and acceleration and pitch, roll and twist accelerations. Horizontal motion of the table is limited to one direction.

The frame was instrumented to measure accelerations, displacements and forces. 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 to the concrete blocks constituting the dead weight of the frame to limit high-frequency noise in the accelerometers.

Displacements were recorded by linear potentiometers with respect to a reference frame located to the left of the model close to the table (see Fig. 2). The horizontal displacements were measured on the base level on either of the two base floor girders and on each floor level. Vertical displacements were measured on all four bearings.

Shear loads were recorded by eight load cells placed under the bearings and the skid system (see Fig. 1). In all, 41 channels of information were gathered; seven of those were table functions and 34 were frame functions.

Data samples were taken at a rate of 50 samples per second for each channel and then stored on magnetic tape.

4. Experimental Program

i) Sinusoidal Tests

The test series began with sinusoidal excitation at different frequencies to evaluate the natural frequency of the isolated system and to estimate the damping. Data were gathered on a limited number of displacements and accelerations and were recorded on a visicorder, which records up to five input channels on photographic paper and has the advantage of providing immediately available results.

Tests were run for a band of frequencies and the natural frequency of the isolated system (assuming largest amplification occurs at resonance) was found to be 0.64 Hz. A run at this frequency was done, the excitation was shut off and the free vibration response was recorded.

The data obtained were analyzed by two different methods. The first method utilized the half-power or bandwidth method which determines the damping ratio from the frequencies at which the response is reduced to $1/\sqrt{2}$ times the amplitude at resonance. The resonance frequency can be determined by this method because for lightly damped systems the peak amplitude occurs at resonance. The resonance frequency thus obtained agreed with the one found before, namely 0.64 Hz and the damping ratio was found to be 5.1% (see Fig. 7).

In the second method the logarithmic decrement in free vibration was used to check the result for the damping ratio. In this method the reduction in amplitude for the free vibration response is used to determine the damping ratio. The result using this method was 5.6% (see Fig. 7), which agreed sufficiently well with the result obtained by the half-power method.

ii) Earthquake Testing Program

Four different earthquake records were used in the testing of the model. They were EL CENTRO N-S (1940), PARKFIELD N65E (1966), PACOIMA DAM S16E (1971) and TAFT (1950). These earthquake records are believed to be representative of California earthquakes.

Geometrical scaling for the model is roughly 1/3 with a corresponding time scaling of $\sqrt{3}$. Tests were run in which the earthquake records were time scaled by the factor $\sqrt{3}$ with the purpose of predicting the response of full scale structures of the type modelled. Tests were also run with the earthquake records unmodified in time. This provides a more severe test of the isolation system and allows verification of analytical work treating the model as a full scale system.

Maximum displacement and acceleration produced by the shaking table can be varied by the SPAN setting which has a direct correlation to the maximum table displacement. A peak table displacement of ± 5 inches - the limit of the table - is given a SPAN number of 1000, while lower SPAN numbers relate to proportionately lower displacements.

The test program summarized in Table 1 shows the SPAN numbers used and the corresponding peak table accelerations for each earthquake and the varying structure conditions. It will be noted that the peak table acceleration for the same earthquake and SPAN number varies considerably. This is because the table motion is displacement controlled and, in addition, there is probably a small amount of structure-table interaction which varies with different base conditions.

Fig. 8 a-d shows the results for the amplification of the acceleration from the table to the various structure levels for all four earthquakes, both in real time and when time scaled by the factor $\sqrt{3}$. The fixed condition, which models a conventional building, shows large amplifications which, in the case of the EL CENTRO and PACOIMA DAM time scaled record are very large causing horizontal accelerations of up to 2.833 g on the fifth floor level. This constitutes an amplification of approximately 4.5 for the EL CENTRO record and 2.8 for the PACOIMA DAM record. The free condition, which models a completely isolated building has, for all four earthquakes, amplification factors which are always less than 1. The reductions in peak acceleration effected by the isolation system range from a factor of 20 in the PACOIMA DAM and EL CENTRO time scaled records to a low of 4 in the PARKFIELD real time record. Since the frame is considered as a 1/3 scale model of a real system the minimum reduction expected in a real system is of the order of that for the PARKFIELD time scaled, which was 15. In addition, the accelerations at the various floor levels vary only very slightly in each case; this clearly indicates that the structure responds to the table excitation as a rigid body.

The several base conditions which involve contact between the fail-safe system and the base beam of the structure are bounded by these two extreme conditions. It should be noted, however, that contact between the frame and the fail-safe system and friction between them does not create large amplifications. The effect of this fail-safe system on the structure is far less severe than might be expected, and amplifications are much less than in the fixed-base, conventional structure. The greatest amplification obtained when the frame was in contact with the fail-safe system was approximately 1.4 (TAFT 300 real time) as compared to the 4.5 for the fixed case. In all other records, real time and time scaled, the peak accelerations were smaller and sometimes considerably smaller than the peak input accelerations.

To obtain more insight into this phenomenon the complete time history of the accelerations of the first to fifth floor level have been plotted for a particular earthquake record (EC 500) and for the different base conditions (see Fig. 9 a-d). It is clear that the fixed-base condition produces increasing amplifications of the accelerations with increasing elevation and the free case structure responds at a much lower frequency (the natural frequency of the structure on the bearings) with no variation of the acceleration at the different floor levels. In the other cases which include contacting the skid system the accelerations are not amplified as functions of floor level and are in fact very close to the free (isolated) case. However, it is apparent from the plots in Fig. 9 that there is a positive correlation between structure-skid system contact and a high frequency response. When the contact takes place high vibrations are induced in the frame. Although these frequencies do not generate high accelerations in the frame and are of no major importance for the structure itself, they may affect internal equipment considerably. This aspect needs further investigation.

To describe the general behavior of the system (frame,bearings, fail-safe system) the sum of the shear forces in the fail-safe system and in the bearings, the relative base displacement and the base and table accelerations were plotted in time history for one representative earthquake (EC500) under the various base conditions (see Fig. 10 a-d). The plots for the fixed-base condition show that the relative base displacement is negligible for the duration of the excitation and the bearings were effectively bypassed by the attached straps. The free condition of the isolated system shows a complete reversal of the effects on the structure. In this case the structure responds at a much lower frequency (the natural frequency of the structure on the bearings) to the table excitation and the accelerations in the structure are very small; however, relative displacements of the whole frame with respect to the table are much larger. The shear forces that are developed in the bearings as a result of these displacements trace the relative displacement almost exactly, indicating the linearity of the force-displacement relation in the bearings. With the action of the fail-safe system included it is clear that the relative displacements are reduced when the frame is contacting the fail-safe system. Correspondingly, the forces in the bearings are reduced as the systems are contacting and forces in the fail-safe system are developed. The high frequencies that were noted earlier can now be seen to develop at the points where the systems are contacting, i.e. when forces in the fail-safe system are being developed. The nature of these forces was studied by plotting them versus the corresponding relative base displacement for a small time interval around the peak displacement (from 6.3 sec to 9.7 sec). In addition, the sum of the shear forces in the bearings was plotted for the same interval (Fig. 11).

The graphs illustrate the difference between the system with and without the operation of the fail-safe system. The bearings alone act as linear viscous dampers with very little damping, the fail-safe system responds as a hysteretic damper with an amount of hysteretic energy loss varying for the different base conditions and for different amplitudes of relative displacement. These hysteretic damping forces are developed as follows: Vertical displacements at the bearings increase non-linearly with increasing horizontal displacements (see static results Fig. 3). As a result, the frame is brought into contact with the fail-safe system and a normal pressure is developed that grows with increasing displacement. This normal pressure results in a transfer of vertical load from the bearings to the skid system. Coulomb frictional forces are developed in the skid system that are proportional to this normal load but in phase with the velocity. The transfer of load is quadratic in the relative displacement and the Coulomb friction force linear in the normal load, leading to the quadratic variation in horizontal skid forces as shown in Fig. 3. It is worth noting that, since these hysteretic damping forces are in phase with the velocity, when the frame velocity changes sign the force reverses suddenly. This discontinuity in the force occurs when the force is a maximum and from Fig. 10 is clearly the cause of the high frequency energy input seen in the acceleration records at every level in the frame. These discontinuities are clear in the force displacement diagrams Fig. 11. To demonstrate this effect of the fail-safe system on the structure 5 plots of the Fourier spectrum (FFT) of the second floor acceleration for the five different base conditions are shown in Fig. 12. The Fourier spectra show how the energy is reduced in the lowest mode and induced in higher modes with increasing contact between the fail-safe system and the frame.

Because the clearance between the frame and the fail-safe system was not completely uniform the hysteretic curve for the sum of the skid forces are not symmetric about the zero displacement axis. As a direct consequence of the relative horizontal displacements being limited by the action of the fail-safe system the sum of the forces in the bearings is diminished from 8.9 kips for the free case to 6.9 kips for the low clearance (LC) case.

iii) Test of Fail-Safe Action

Examination of the peak response results shown in Fig. 8 indicates that the most damaging input from the point of view of the base isolation system is that derived from the PARKFIELD N65E (1966) record. At first sight this is surprising in that the peak acceleration of this record is not great and the published response spectrum of the record does not show any significant characteristics around the 0.64 Hz natural frequency of the isolation system. However the input to the shaking table is produced by manipulation of the published acceleration record. The table is displacement controlled and the displacement input is altered from that displacement time history computed by integration of the earthquake acceleration record to provide a signal which is balanced in peak positive and negative displacement. This is done to make full use of the displacement limits of the table motion. A comparison of the table displacement (Fig. 13) and the published displacement record of the real earthquake [9] show the considerable differences that have been produced between these two records in the initial interval although the table acceleration record is very similar to the real record. This introduces a spurious low frequency modification of the signal which is normally of no importance. In the earlier part of the table displacement record, up to about 8 secs the dominant frequencies are below 1 Hz as shown in the FFT (Fig. 13) of the displacement in this interval. The model exhibits a series of three almost perfect sine waves of linearly increasing amplitude, characteristic of resonance. This low frequency input is not in the real PARKFIELD record and the result is not predictive of how the isolation system would respond in real earthquakes but it provides a signal which can readily be used to assess the fail-safe characteristics of the system within the limits of the table motions. The peak acceleration in the table signal which also occurs during this interval has almost no effect on the model response; the critical factor is the maximum displacement in this initial interval.

For this reason the PARKFIELD record was selected to verify the action of the fail-safe system. The input signal was progressively increased from 350 span to 650 span at which level the bearings exceeded their stability limit. The response in this run is shown in Figs. 14 through 16. The bearings are connected to the frame and to the underlying load cells in such a way that tension cannot be developed, the shear force being transmitted by circular disks which act as shear keys. At about 7 secs of the 650 span run the bearings became unattached to the frame due to relative horizontal displacement in excess of 6 inches the stability limit for which the bearins were designed. The frame was then carried on the skid system sliding back and forth and eventually coming to rest. Higher accelerations were developed in the superstructure as shown in Fig. 15.

Only minor damage to the bearings was caused during this operation. One layer of one bearing became delaminated. This layer was replaced and the system was readily reassembled on the table and testing continued. No further such extreme tests were attempted to avoid the possibility of damage to sensitve instrumentation such as accelerometers and potentiometers.

5. Conclusions

It has been shown that with ground excitation the accelerations a building is subjected to can be effectively reduced by isolating the building on rubber bearings. The accelerations are smaller than the ground acceleration and no amplification of acceleration takes place at the various levels of the building. This advantage is offset by the problem of larger relative displacements; however, the size of these displacements can be controlled by including the proposed fail-safe system. The adjustment of the fail-safe system for different clearances was difficult throughout the testing because the desired clearance is sensitive to slight adjustments in the height of the fail-safe system. The tests, however, clearly show that finely adjusted clearances are not a critical factor in the response; even with very low clearance, i.e. fail-safe system and frame touching at zero displacement, there was no great increase in peak accelerations in the structure, and only very limited amplification. The only aspect that caused some concern was the fact that the action of the fail-safe system apparently induced some high frequency input into the structure. Although this is certainly not a major problem for the structure itself, it might become a problem for internal equipment, and this aspect needs further investigation. The tests also clearly show that the fail-safe system can be used effectively as a Coulomb friction damper for the structure, thus controlling the response of the structure. The test of the fail-safe action of the proposed skid system shows that collapse of the structure is prevented. After the stability limit of the bearings is exceeded and they fail the structure is completely carried by the fail-safe skid system which then provides a large sliding frictional force limiting the response under these extreme conditions.

Previously proposed systems are subject to very large relative horizontal displacements and possible building collapse in the event of an unexpectedly large earthquake creating relative horizontal displacements exceeding the stability limit of the bearings. These shortcomings are corrected for in the system described, and no major obstacles are seen for incorporating the proposed system into a real structure, where the skid system would most conveniently be designed as a split foundation system; two layers, most likely of reinforced concrete separated by a small gap. In the opinion of the authors the method of isolating structures on rubber bearings and including a fail-safe system that also acts as a hysteretic damper is a very practical and cost-effective way of designing earthquake-safe builidngs.

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EARTHQUAKE	SPAN	CLEARANCE	ABSOLUTE MAX. TABLE ACC. (g)
EL CENTRO (real time)	500	FREE	.318
	"	HC - 2" contact	.274
	"	MC - 1" "	.308
	"	LC - 0" "	.314
	"	FIXED	.365
EL CENTRO (time scaled by √3)	200	FREE	.491
	"	HC - 2" contact	.459
	"	MC - 1" "	.539
	"	LC - 0" "	.473
	"	FIXED	.555
TAFT (real time)	300	FREE	.175
	"	HC - 2" contact	.181
	"	MC - 1" "	.180
	"	LC - 0" "	.173
	"	FIXED	.194
TAFT (time scaled by √3)	350	FREE	.525
	"	HC - 2" contact	.476
	"	MC - 1" "	.542
	"	LC - 0" "	.485
	"	FIXED	.588
PACOIMA	250	FREE	.293
	"	HC - 2" contact	.295
	"	MC - 1" "	.284
	"	LC - 0" "	.300
	"	FIXED	.326
PACOIMA (time scaled by √3)	300	FREE	1.218
	"	HC - 2" contact	1.147
	"	MC - 1" "	1.225
	"	LC - 0" "	1.244
	"	FIXED	1.047
PARKFIELD (real time)	350	FREE	.160
	"	HC - 2" contact	.146
	"	MC - 1" "	.156
	"	LC - 0" "	.169
	"	FIXED	.168
PARKFIELD (time scaled by √3)	300	FREE	.364
	"	HC - 2" contact	.341
	"	MC - 1" "	.356
	"	LC - 0" "	.352
	"	FIXED	.379

Table 1: Earthquake Test Program

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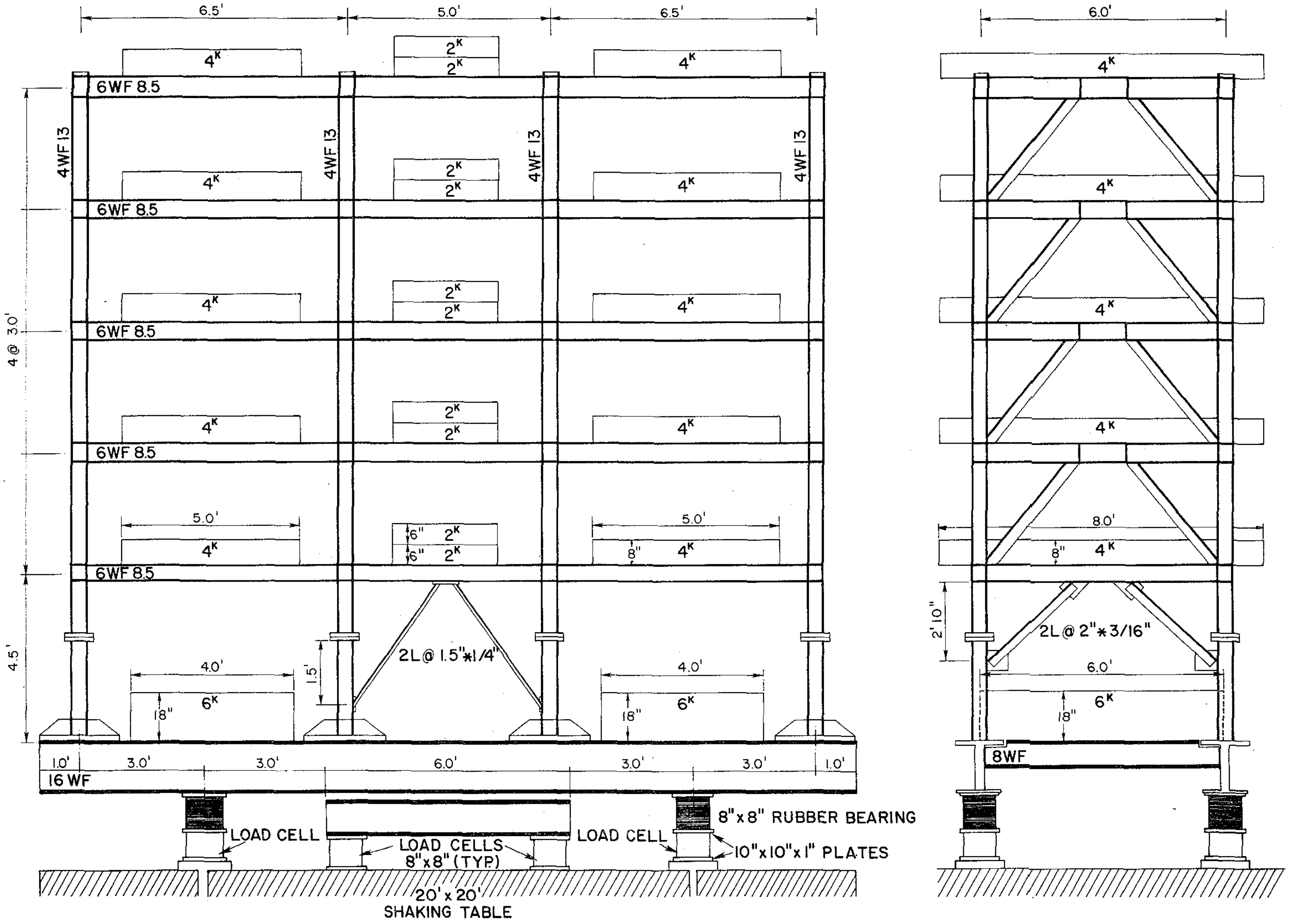


Fig. 1. One Third Scale Structural Model Showing Main Dimensions and Isolation Mounting.

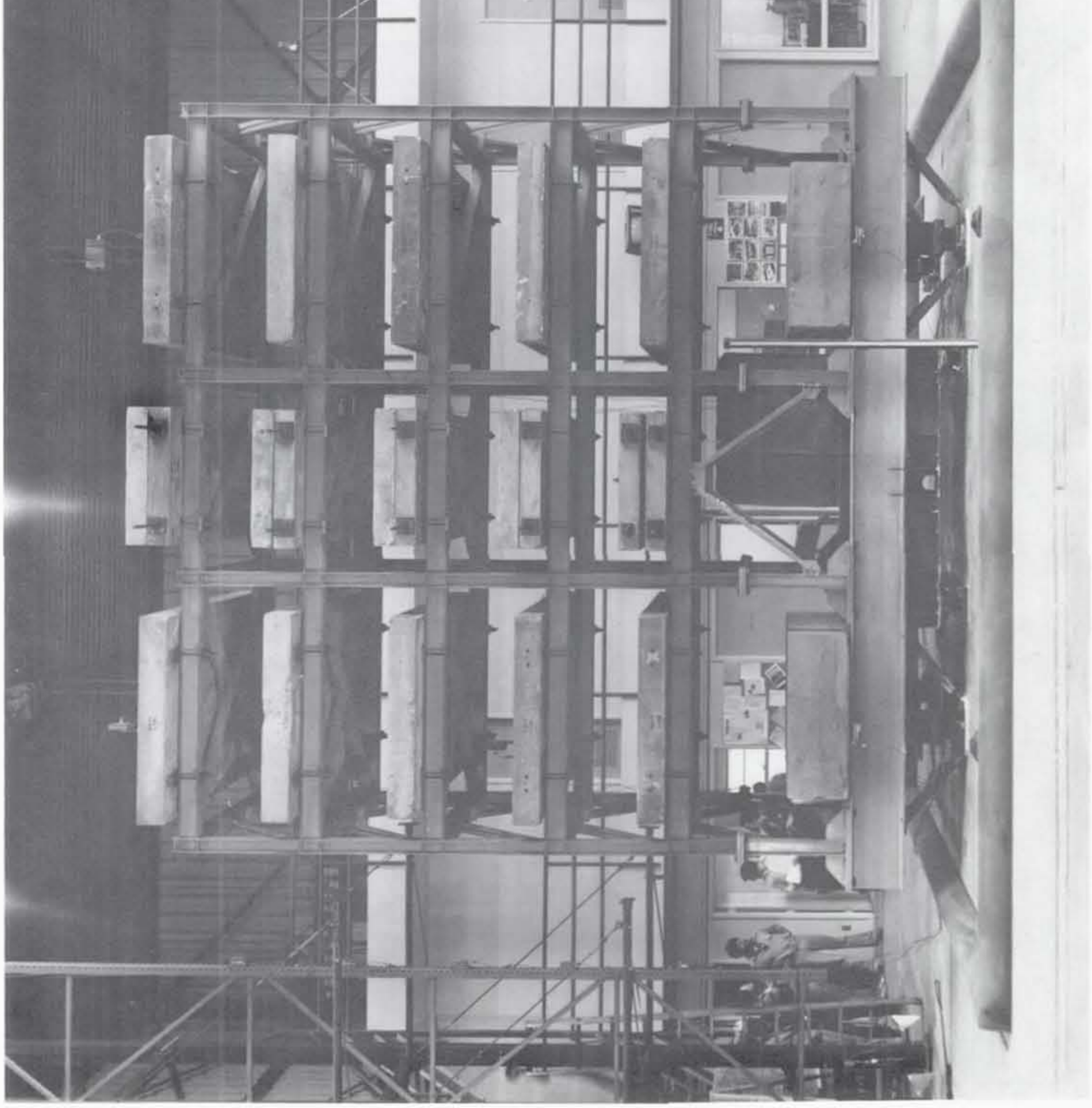


Fig. 2. Structural Model on Shaking Table

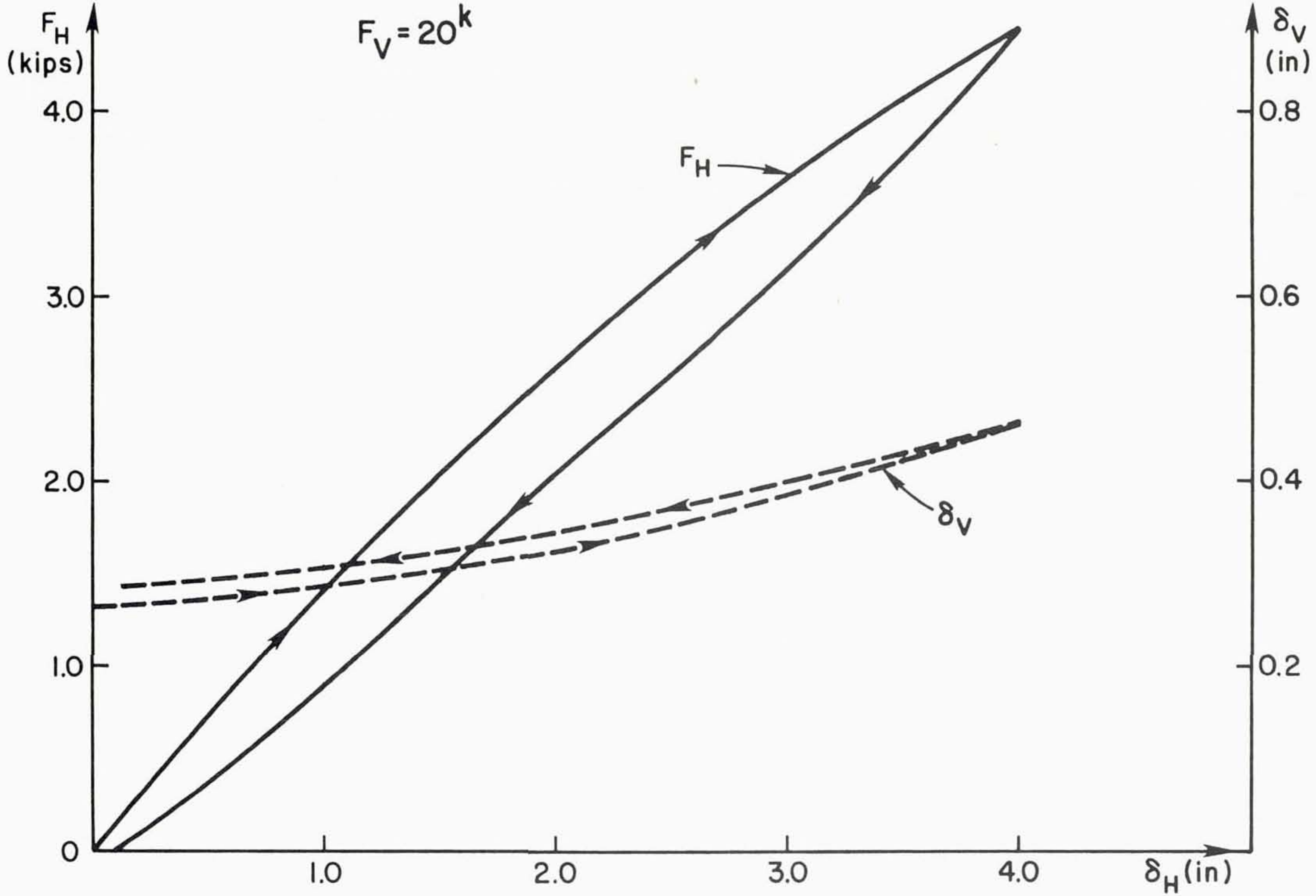


Fig. 3 Load-Displacement Curves; Two Bearings Under 20^k Vertical Load

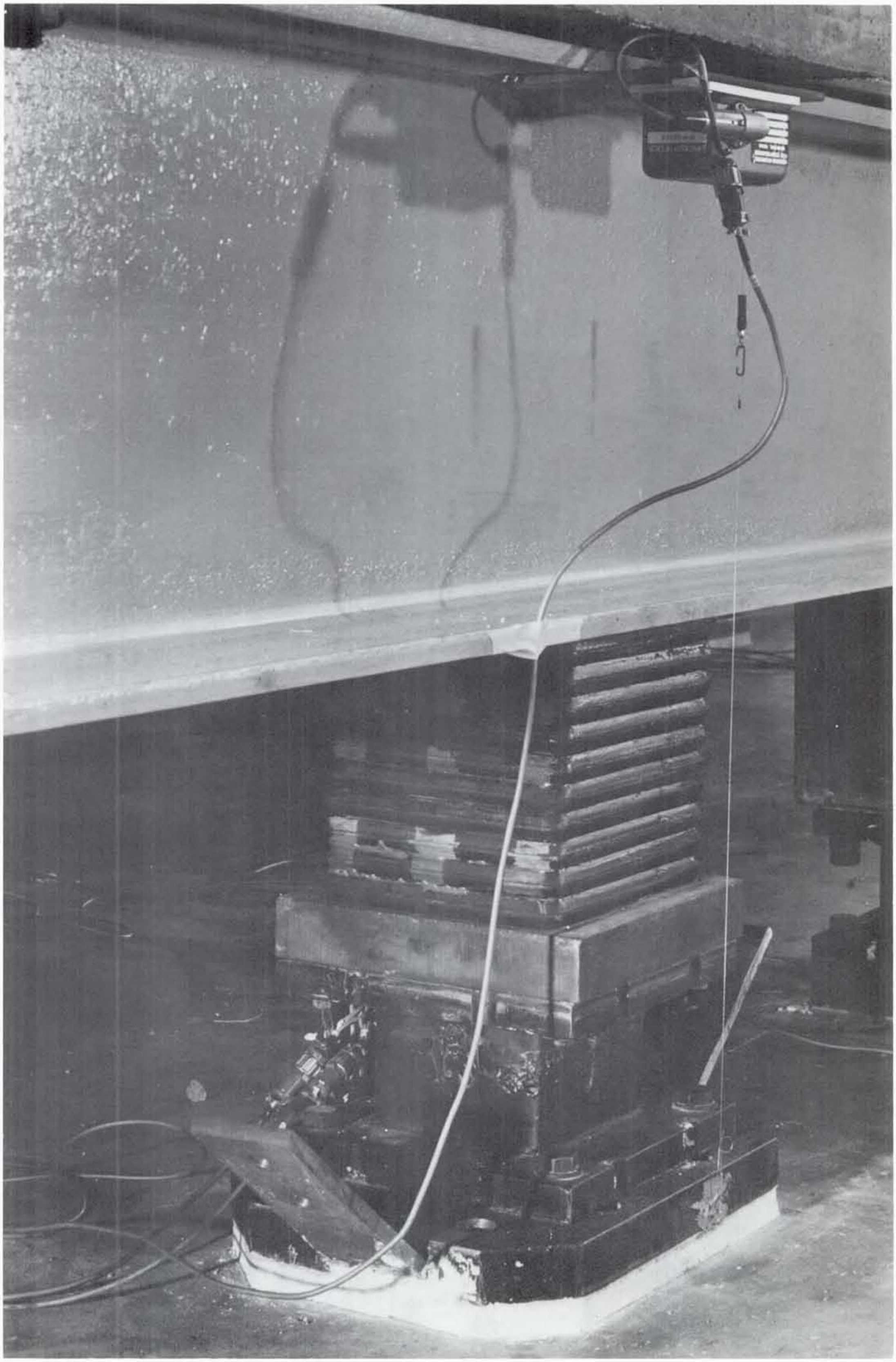


Fig. 4. Isolation Bearings Installed Under Frame on Shaking Table

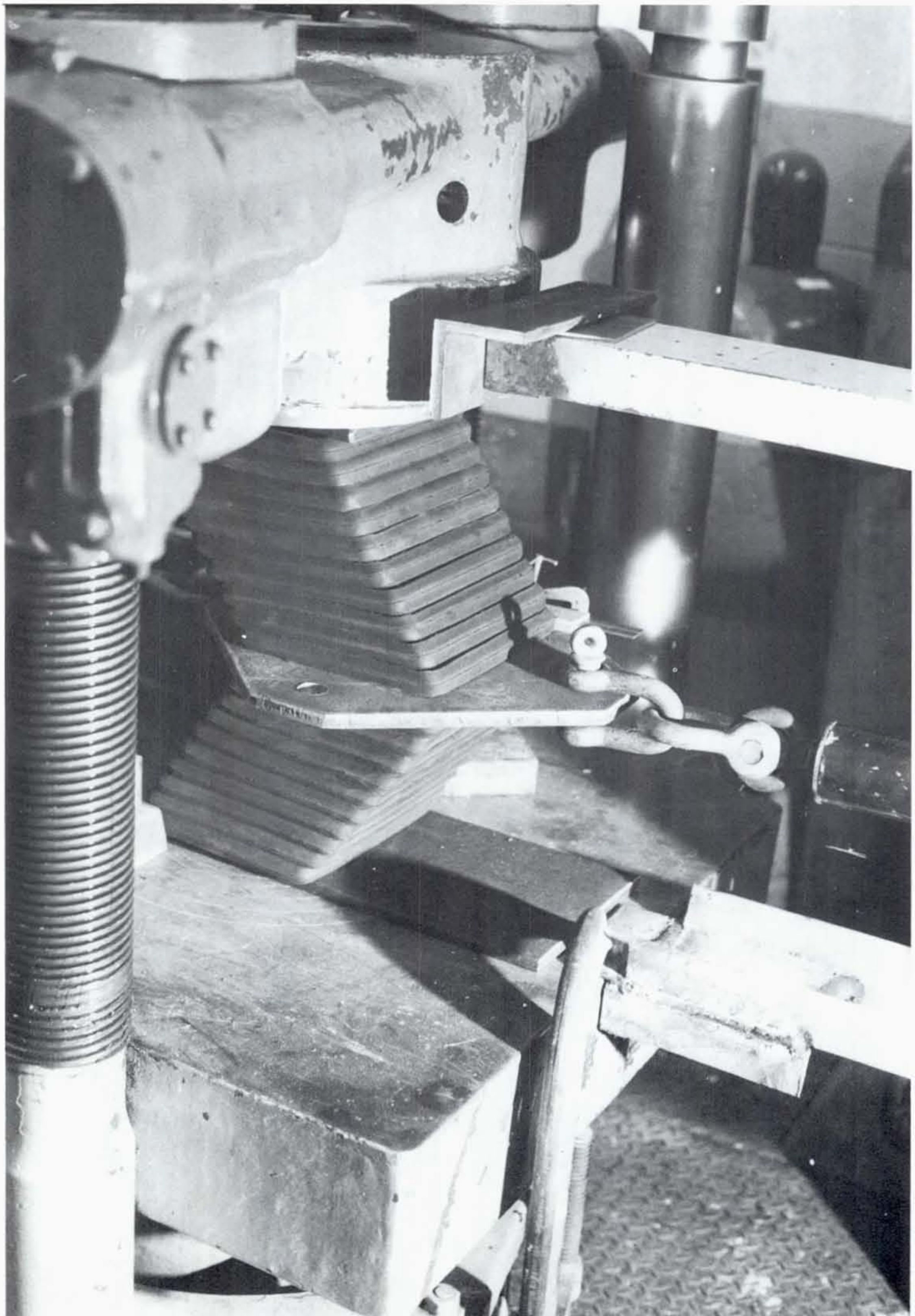


Fig. 5. Apparatus for Static Testing of Isolation Bearings

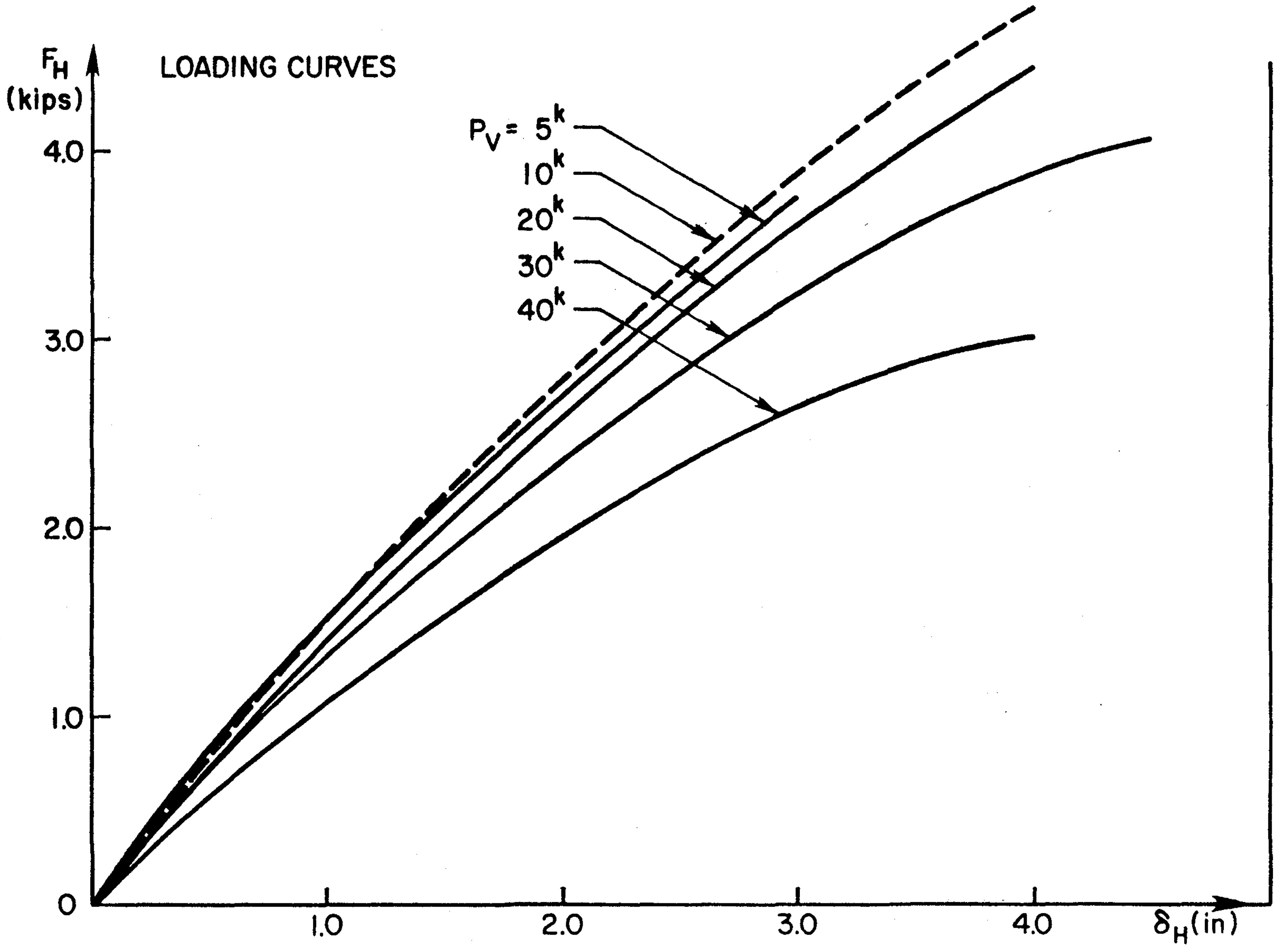
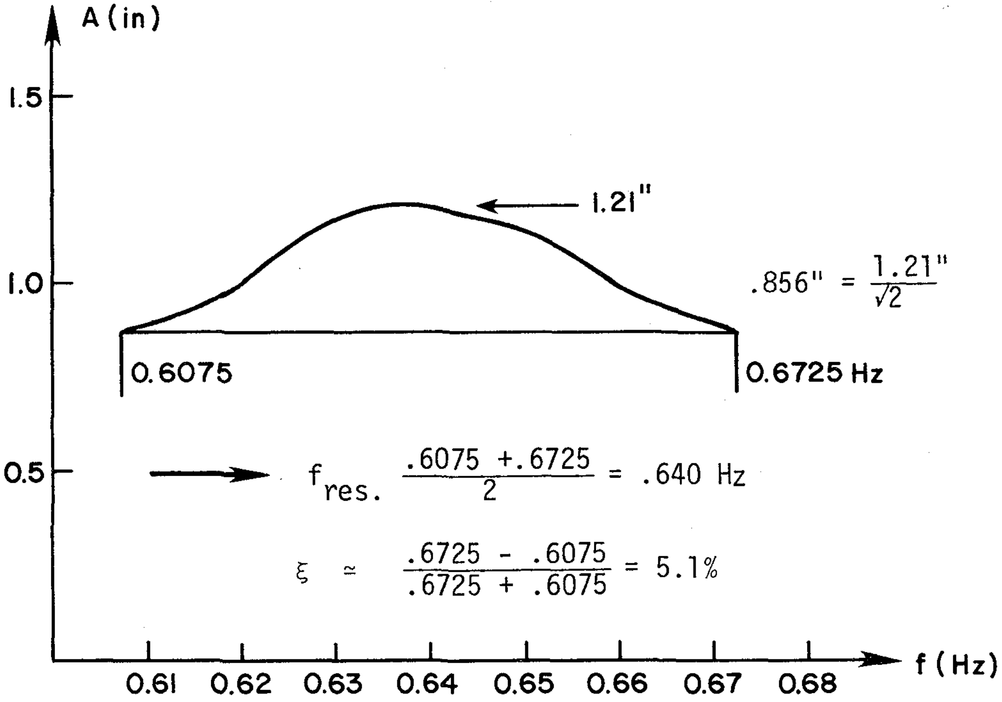


Fig. 6 Stiffness Characteristics of Two Bearings Under Static Loading

Approximate Evaluation of Damping in the Isolated System

(data from visicorder plots)

Half-Power Method



$$.856'' = \frac{1.21''}{\sqrt{2}}$$

$$f_{res.} \quad \frac{.6075 + .6725}{2} = .640 \text{ Hz}$$

$$\xi \simeq \frac{.6725 - .6075}{.6725 + .6075} = 5.1\%$$

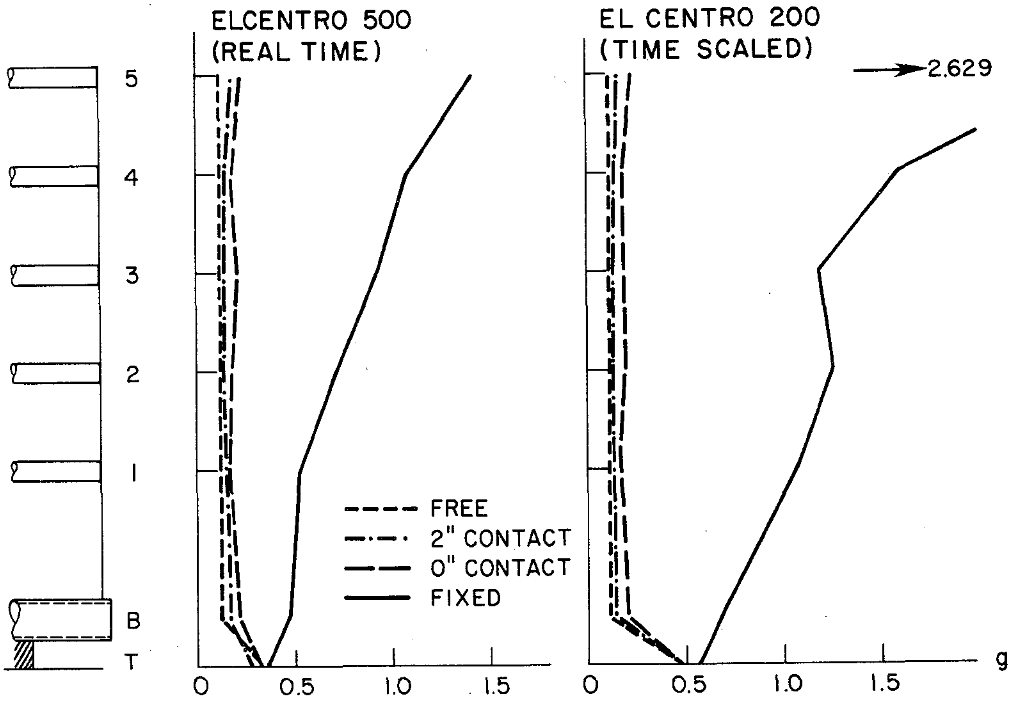
Logarithmic Decrement

assuming $\omega_D = \omega\sqrt{1-\xi^2} \simeq \omega$

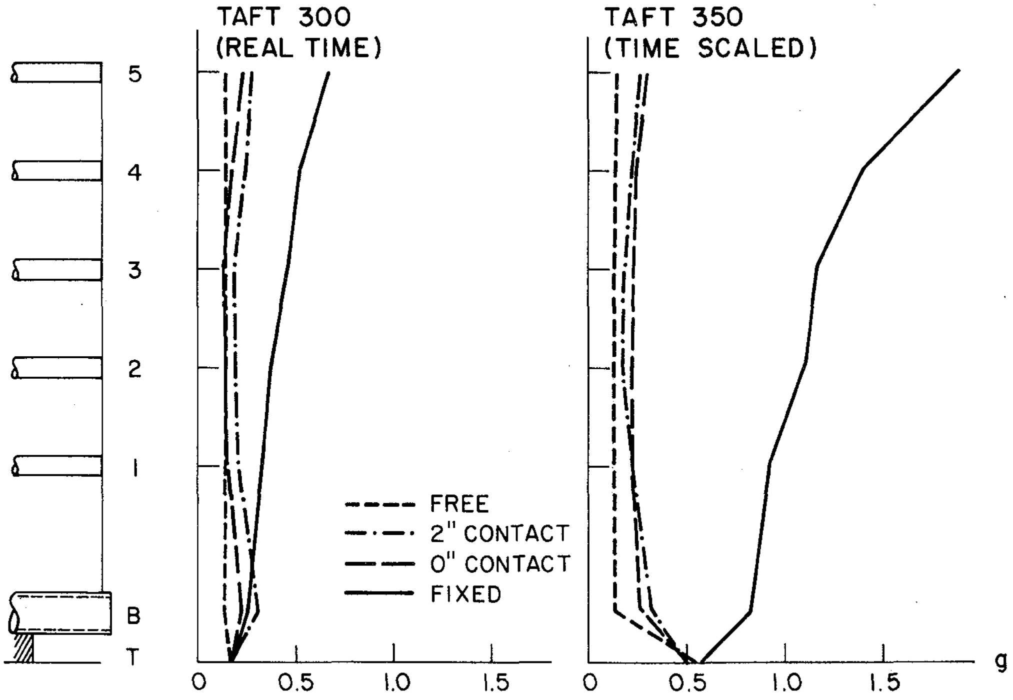
$$\xi \simeq \frac{1}{2\pi} \ell n \frac{V_n}{V_{n+1}} = \frac{1}{2\pi} \ell n \frac{0.8}{0.5625}$$

$$\therefore \quad \xi \simeq 5.6\%$$

Fig. 7. Approximate Evaluation of Damping in the Isolation System (Bearings only).

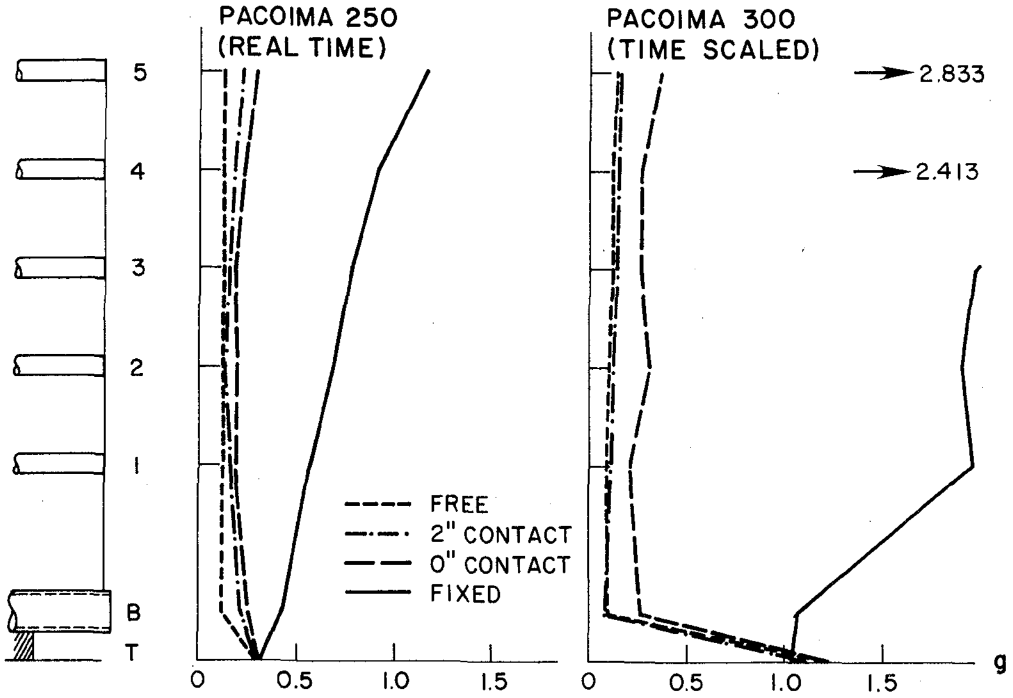


8(a) El Centro in Real Time and Time Scaled

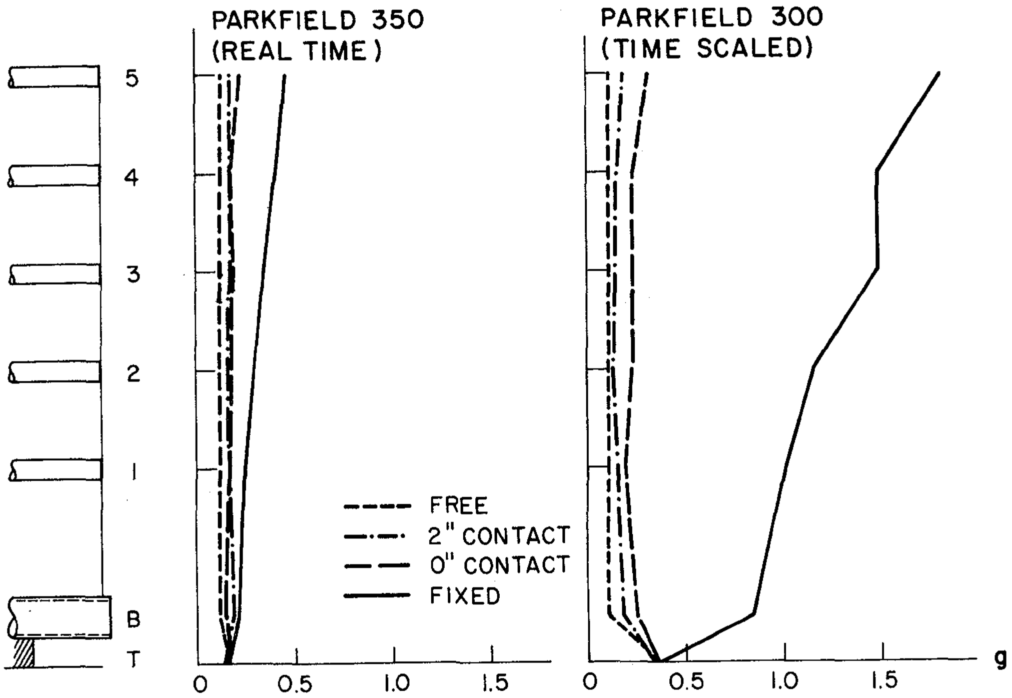


8(b) Taft in Real Time and Time Scaled

Fig. 8. Measured Peak Accelerations at Each Floor Level for Different Base Conditions.



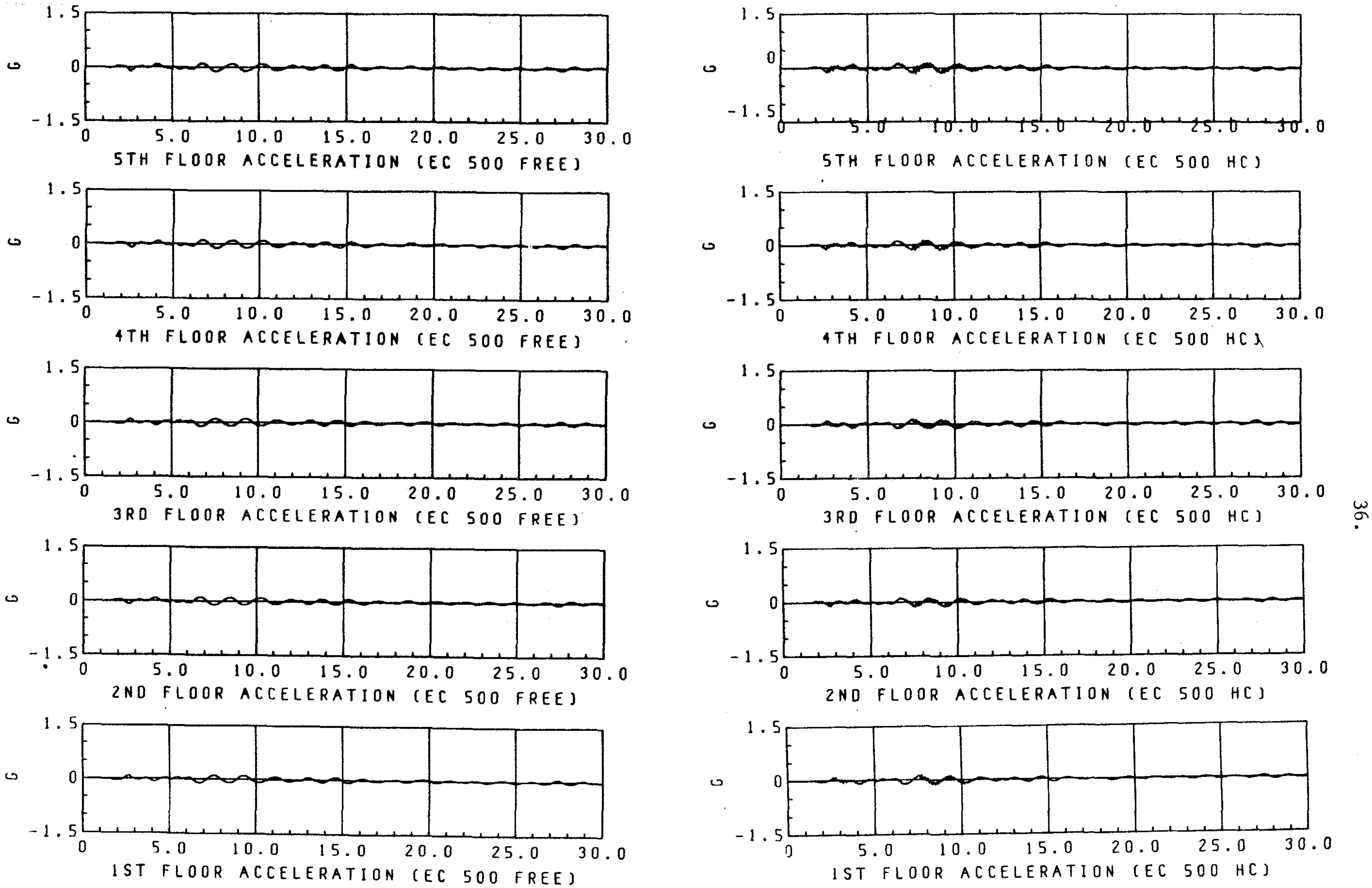
8(c) Pacoima in Real Time and Time Scaled



8(d) Parkfield in Real Time and Time Scaled

Fig. 8. Measured Peak Accelerations at Each Floor Level for Different Base Conditions.

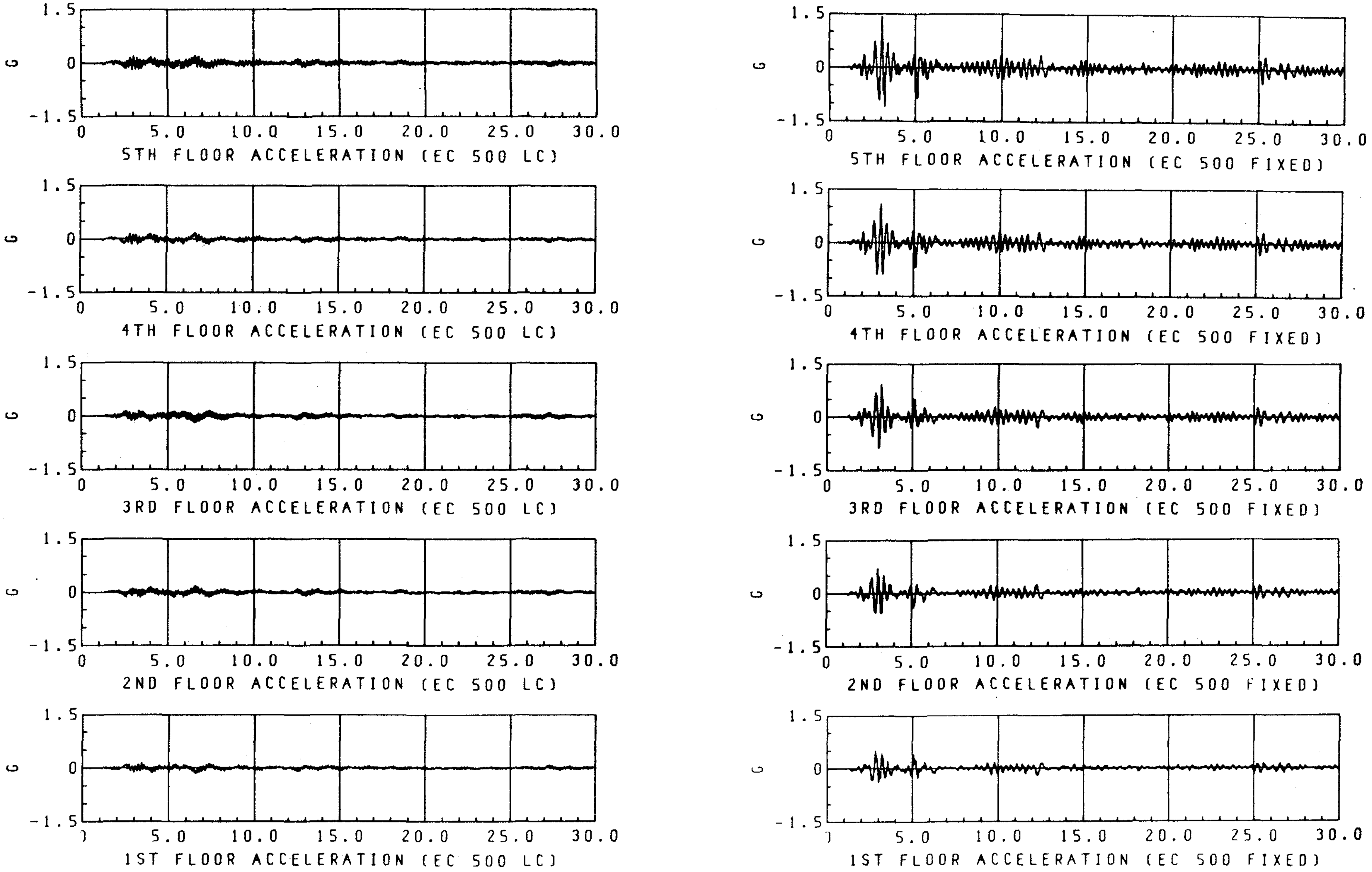
TEST RESULTS



9 (a) Free

9 (b) High Clearance

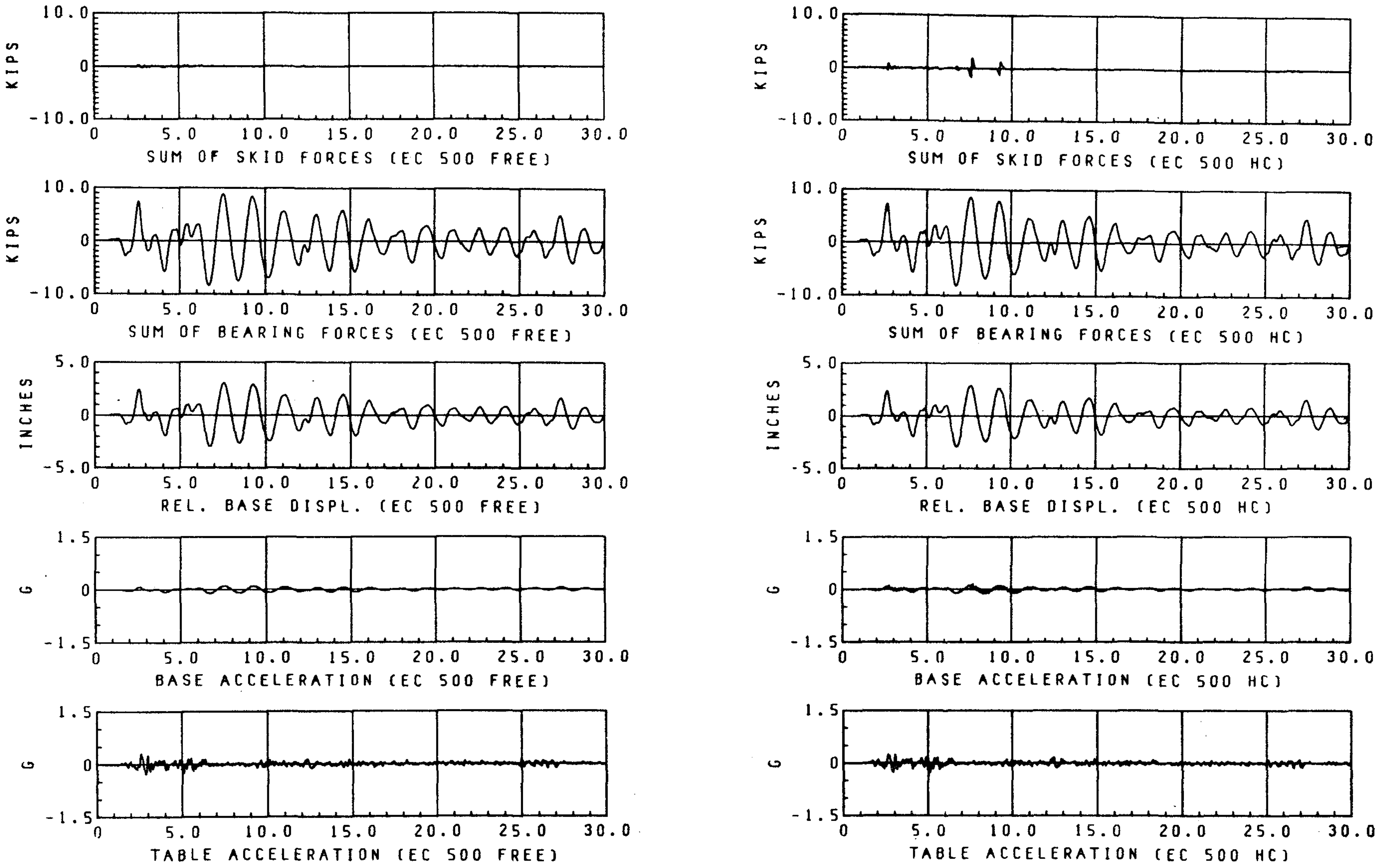
Fig. 9 Measured Accelerations for EL CENTRO 500 for Different Base Conditions



9 (c) Low Clearance

9 (d) Fixed Base

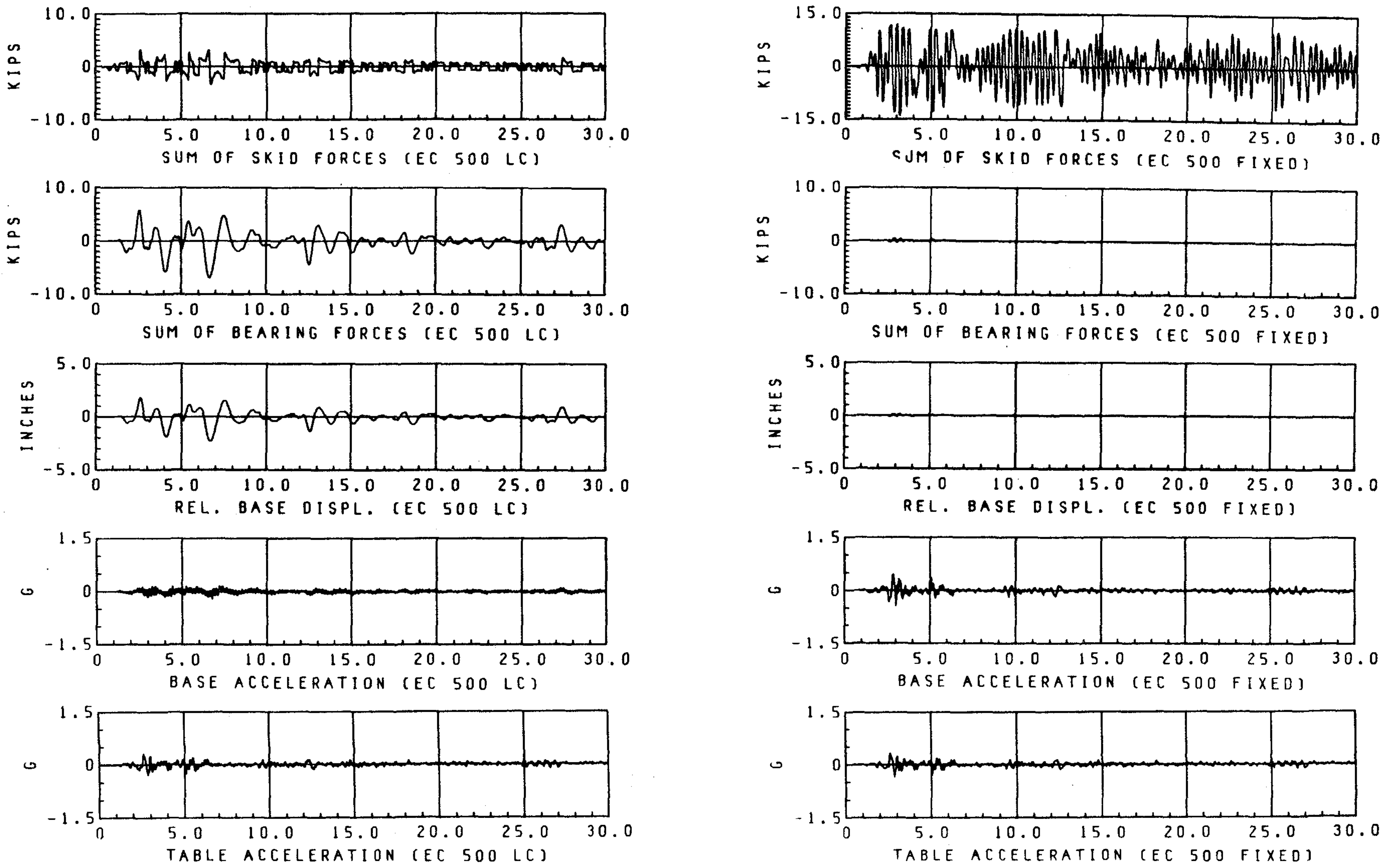
Fig. 9 Measured Accelerations for EL CENTRO 500 for Different Base Conditions



10 (a) Free

10 (b) High Clearance

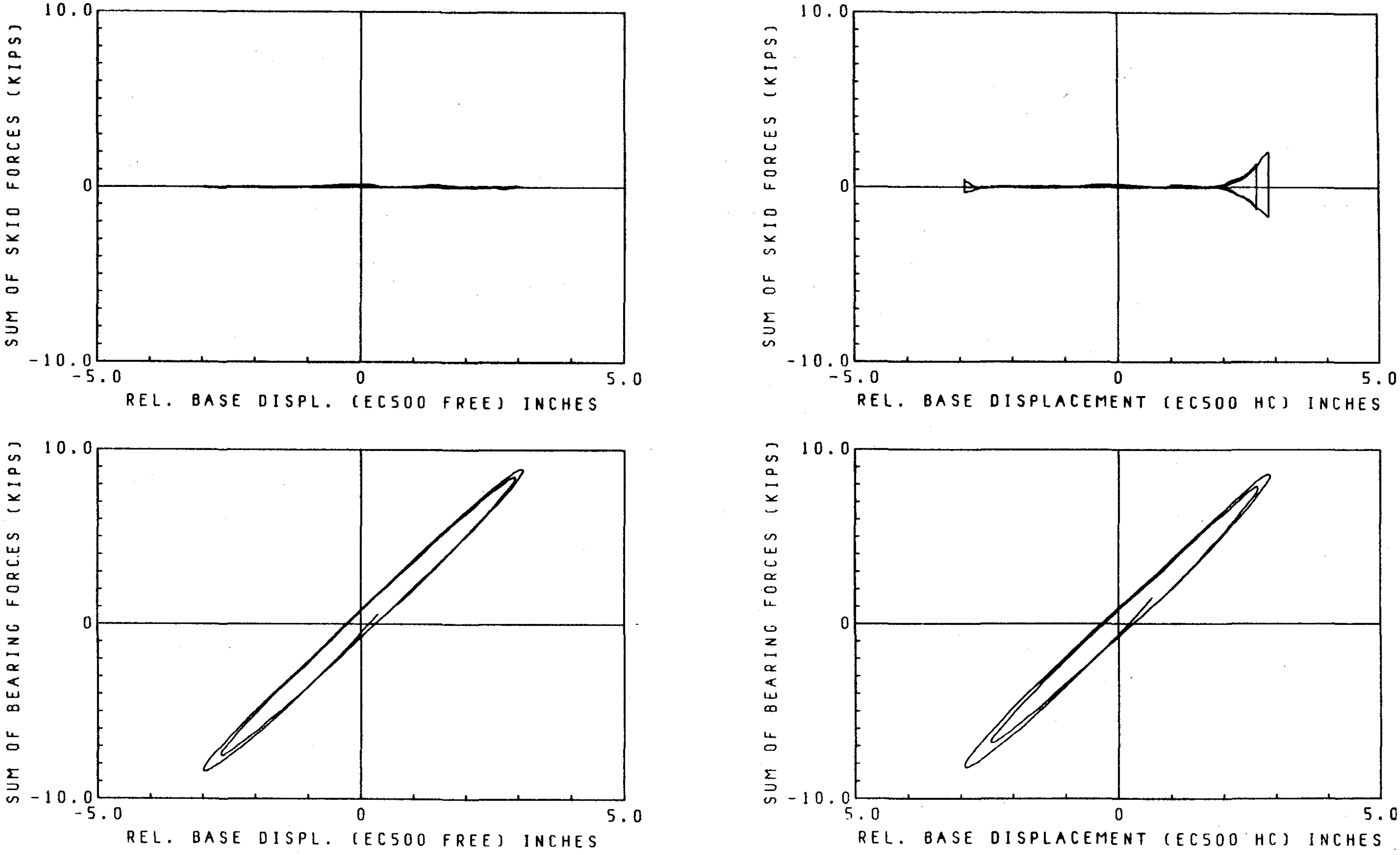
Fig. 10 Isolation System Forces and Displacements for EL CENTRO 500
for Different Base Conditions



10 (c) Low Clearance

10 (d) Fixed Base

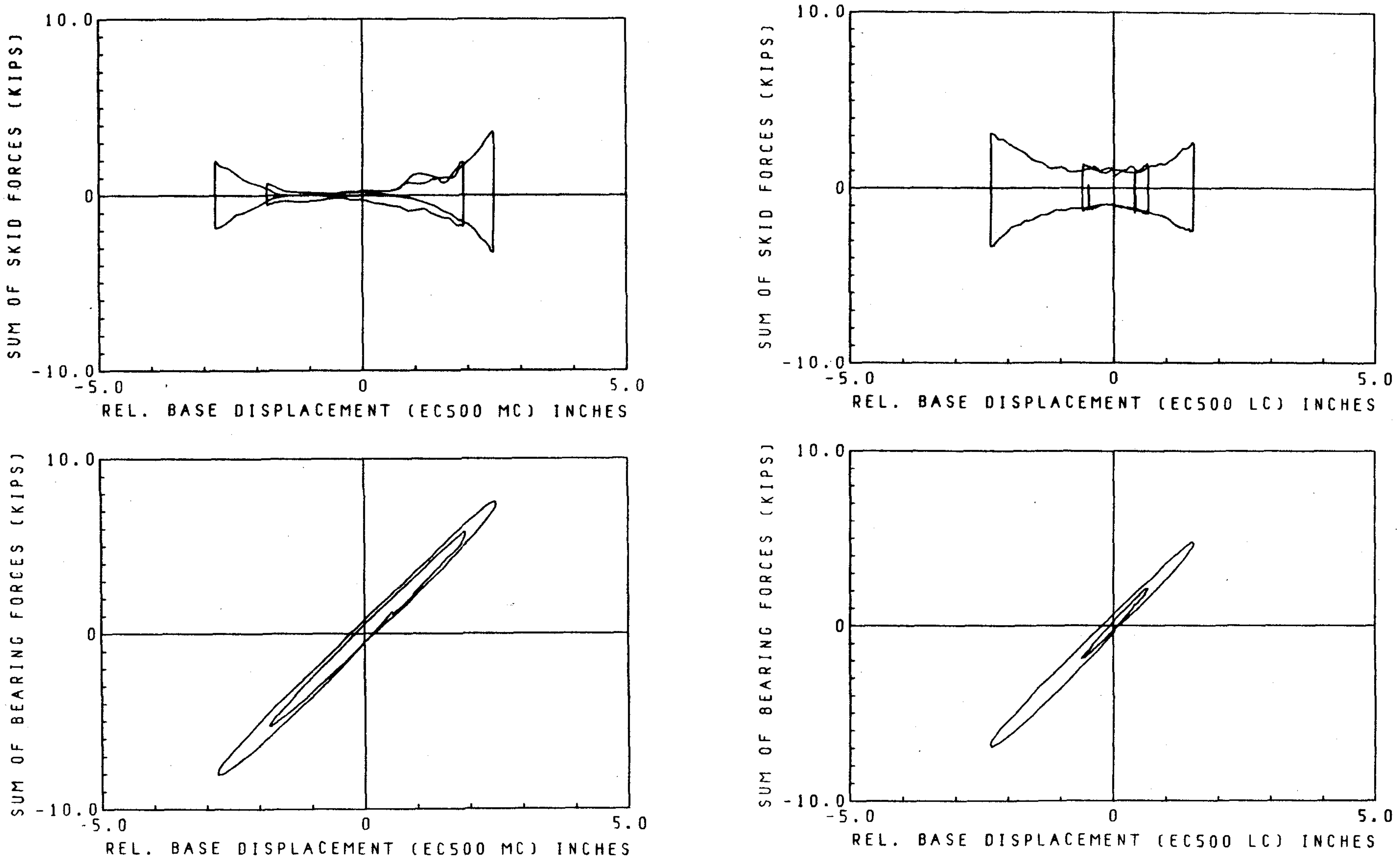
Fig. 10 Isolation System Forces and Displacements for EL CENTRO 500 for Different Base Conditions



11 (a) Free

11 (b) High Clearance

Fig. 11 Force Displacement Curves for Skid System and Bearings under EL CENTRO 500



11 (c) Medium Clearance

11 (d) Low Clearance

Fig. 11 Force Displacement Curves for Skid System and Bearings under EL CENTRO 500

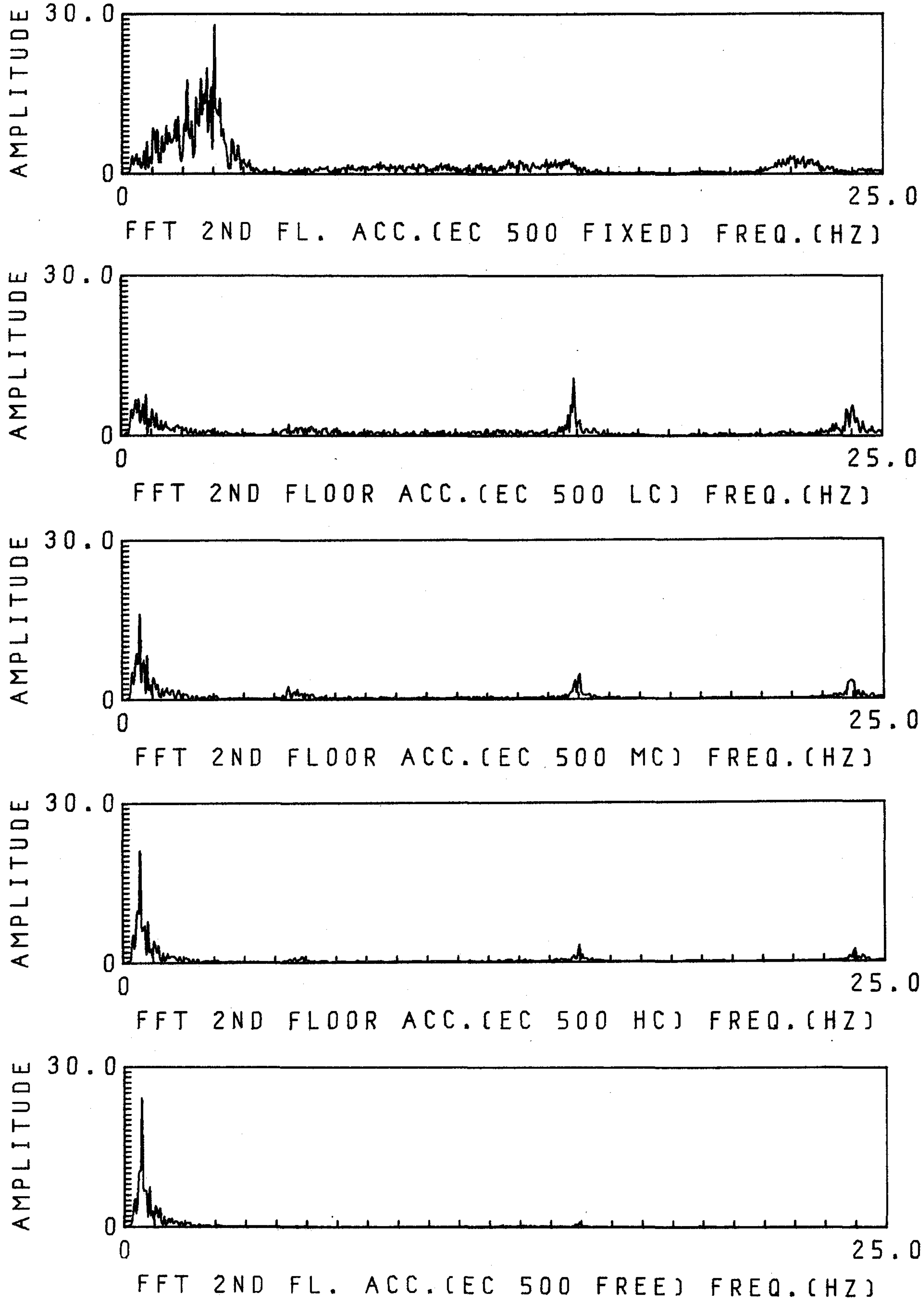


Fig. 12. Fourier Transforms of 2nd Floor Accelerations Showing Influence of Different Base Conditions.

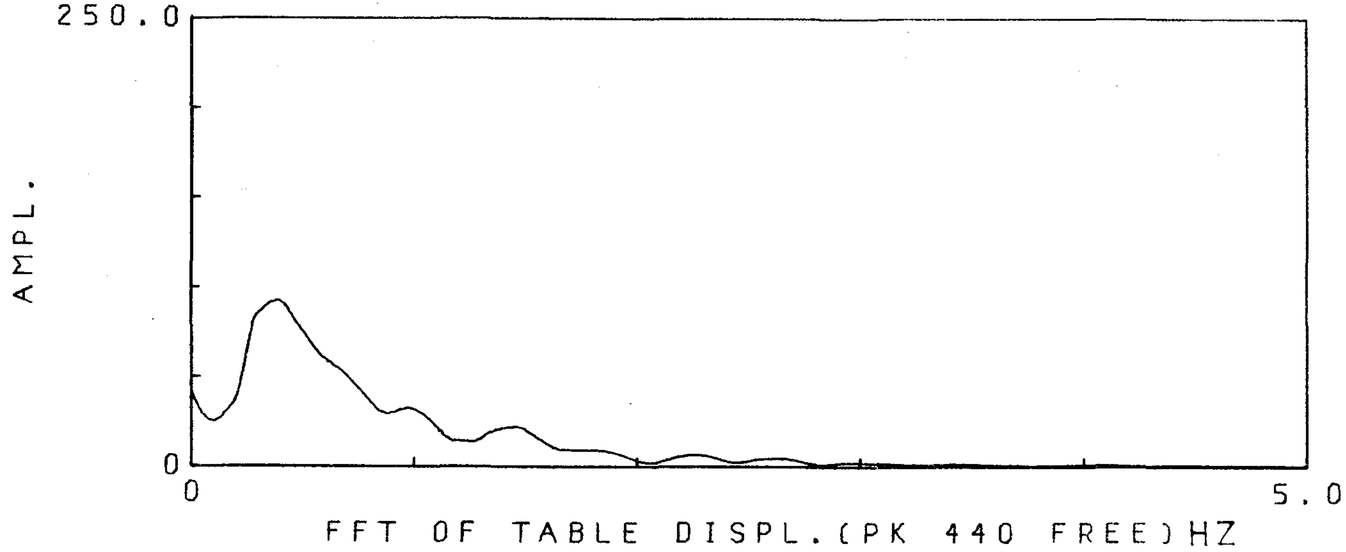


Fig. 13 (b) Fourier Transform of the First 8 Seconds of PARKFIELD Excitation

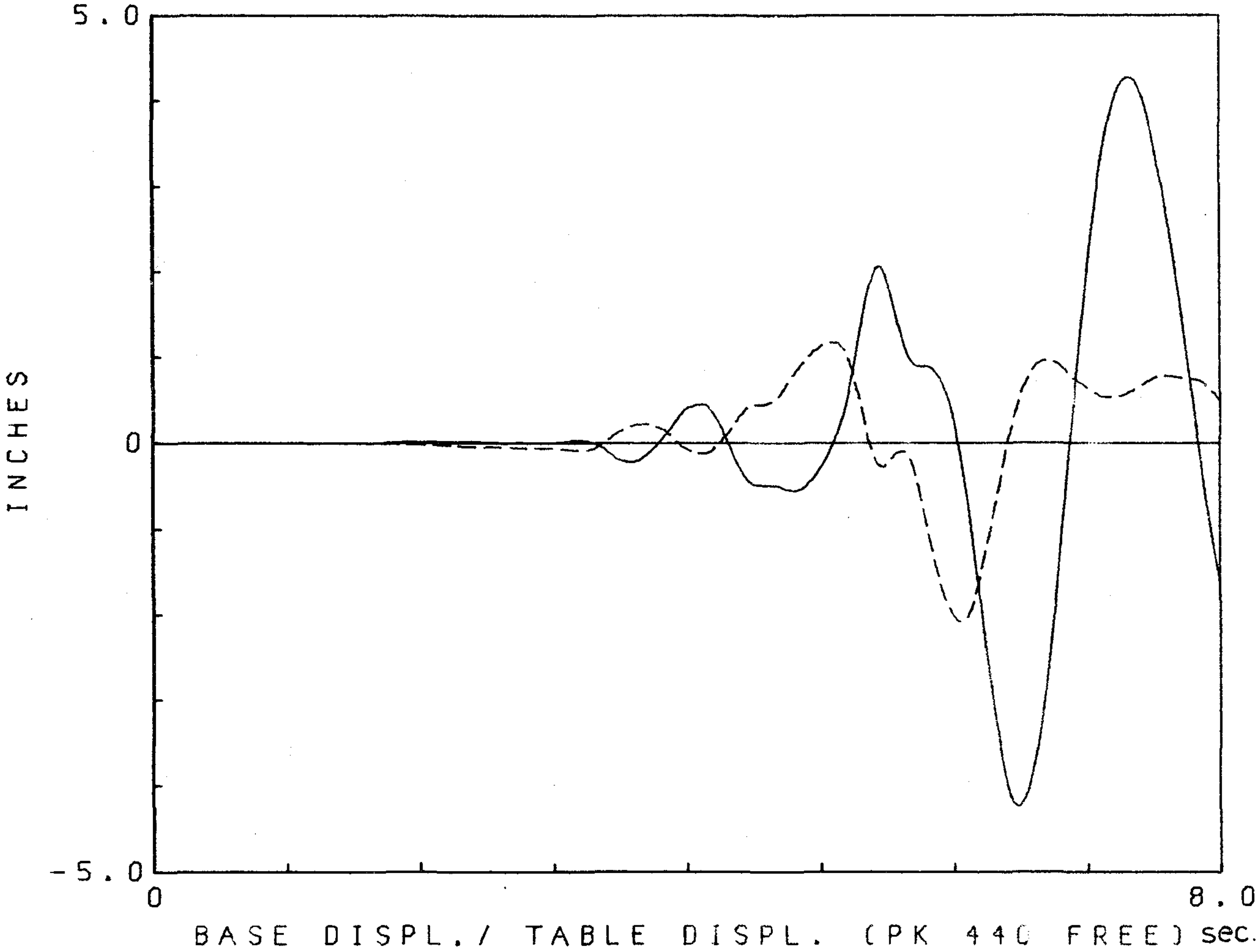
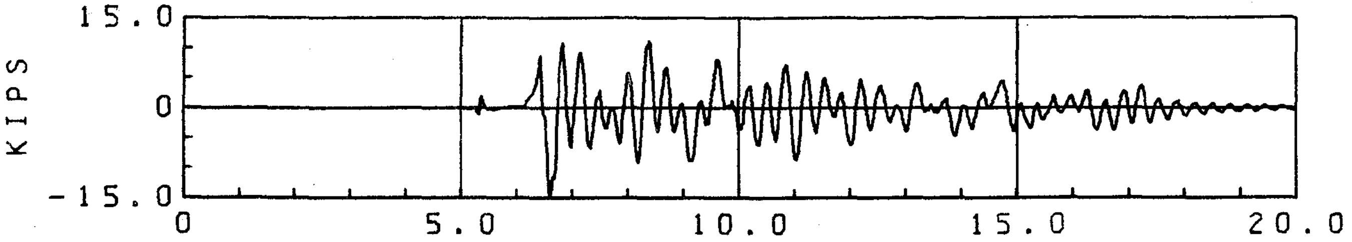
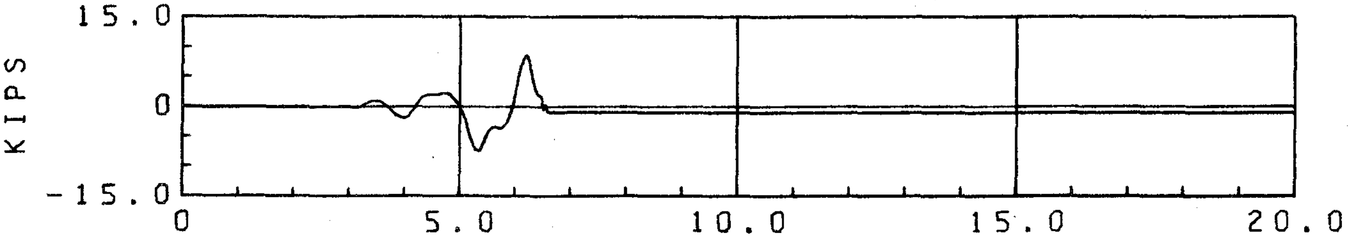


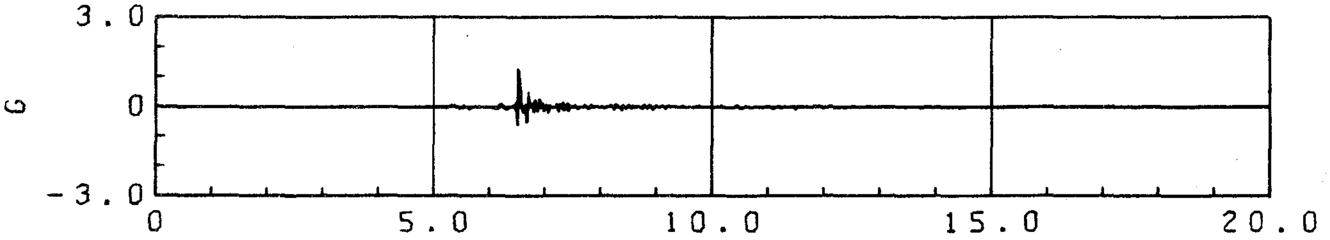
Fig. 13 (a) Superposition of PARKFIELD Excitation and Frame Response



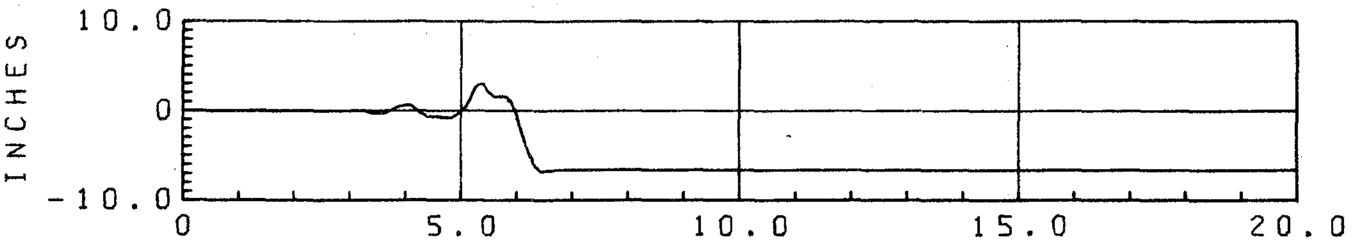
SUM OF SKID FORCES (PK 650 MC)



SUM OF BEARING FORCES (PK 650 MC)



SUM OF VERTICAL ACCELERATION (PK 650 MC)



REL. BASE DISPLACEMENT (PK 650 MC)

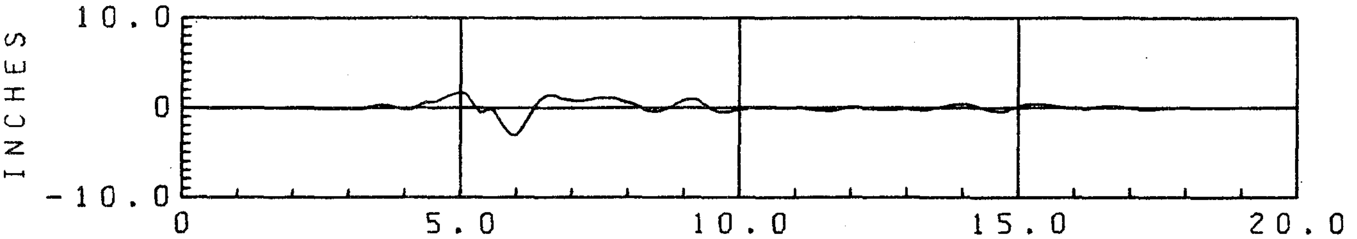
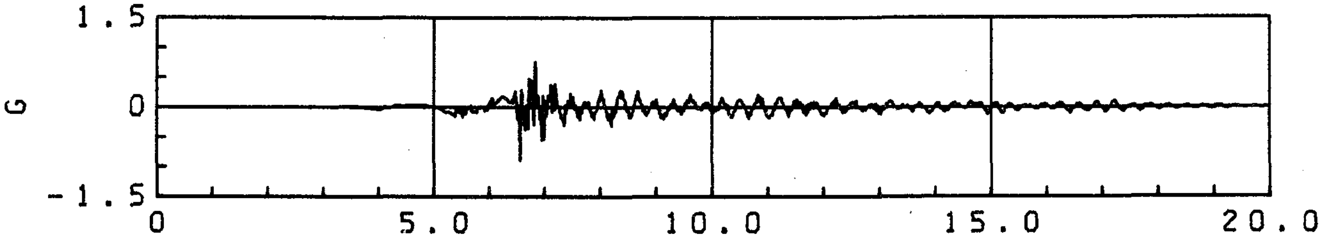
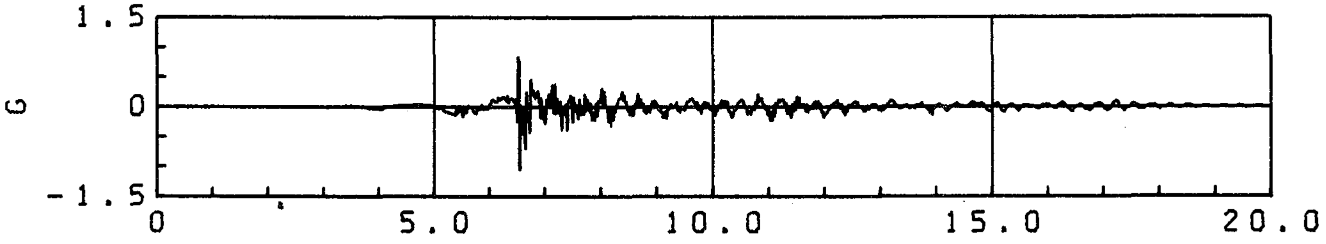


TABLE DISPLACEMENT (PK 650 MC).

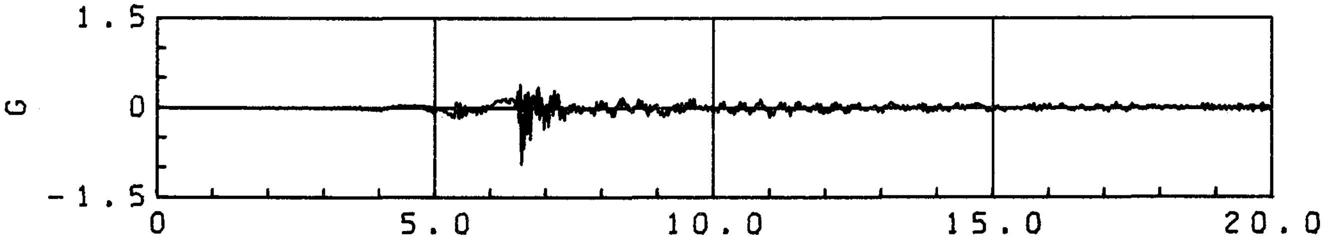
Fig. 14 Results for PARKFIELD 650 Run including Action of the Fail-Safe System



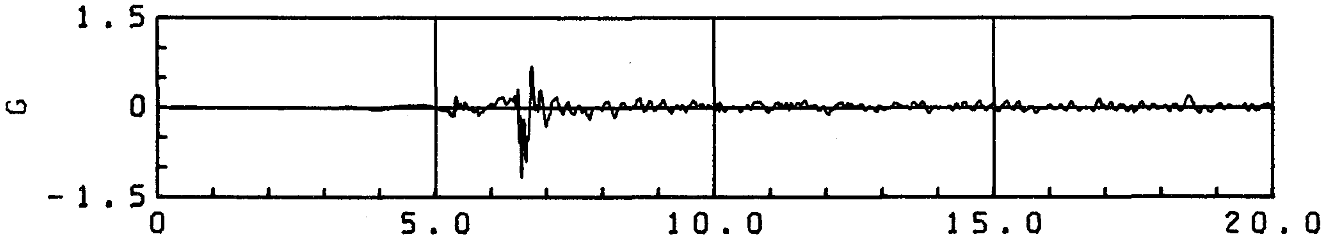
4TH-FLOOR ACCELERATION (PK 650 MC)



3RD-FLOOR ACCELERATION (PK 650 MC)



1ST-FLOOR ACCELERATION (PK 650 MC)



BASE ACCELERATION (PK 650 MC)

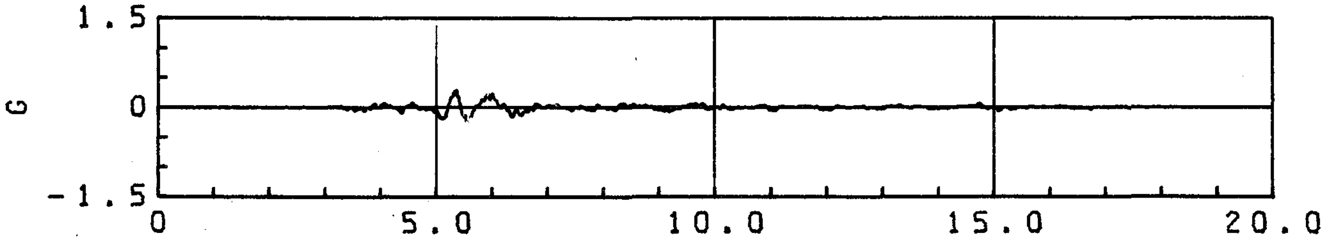


TABLE ACCELERATION (PK 650 MC)

Fig. 15 Accelerations at Different Structure Levels for PARKFIELD 650 Run

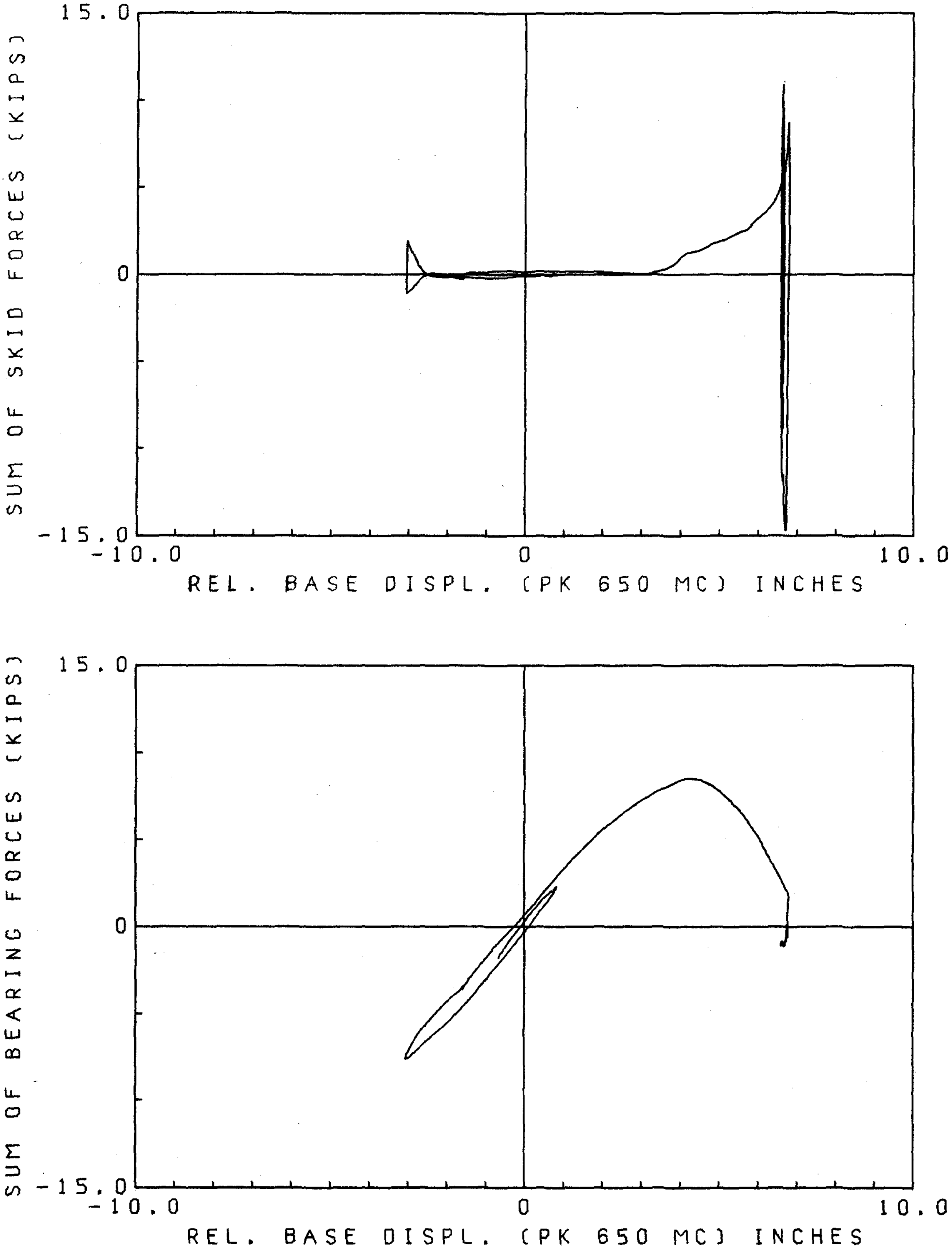


Fig. 16 Interval of Bearing and Skid Forces around Failure of the Bearings

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