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EXPERIMENTAL RESULTS OF AN EARTHQUAKE ISOLATION SYSTEM USING NATURAL RUBBER BEARINGS

by

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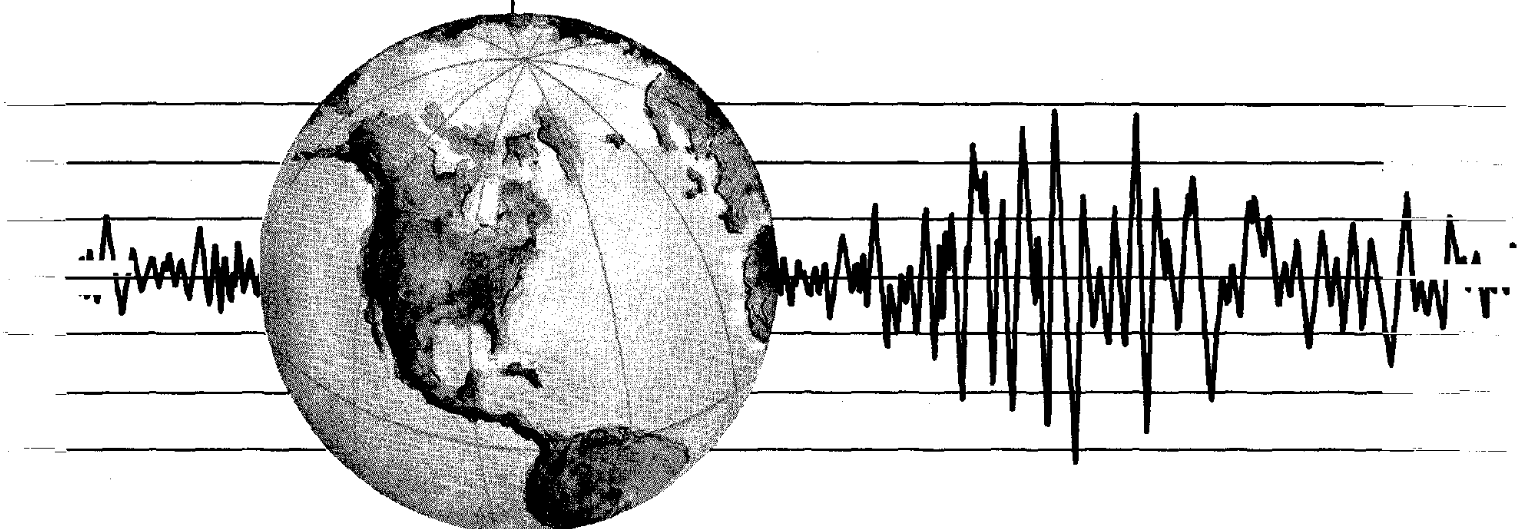
and

J. M. KELLY

Report to National Science Foundation



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This report describes the experimental results of a series of earthquake simulation tests on an earthquake isolation system based on natural rubber bearings. Three forms of isolation system were used. As the primary purpose of the test program was to examine the effect of damping in the isolation system, the essential difference between the three forms was the level of the damping in the system.

A large number of simulated earthquake motions were used in the tests including El Centro 1940, Taft 1950, Parkfield 1966 and Pacoima Dam 1971. The natural rubber bearings reduced the forces and overturning moments to approximately one tenth of those in a conventionally fixed structure and the results demonstrated the practical possibility of this type of isolation system for full scale buildings.

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ABSTRACT

This report describes the experimental results of a series of earthquake simulation tests on an earthquake isolation system based on natural rubber bearings. Three forms of isolation system were used. As the primary purpose of the test program was to examine the effect of damping in the isolation system, the essential difference between the three forms was the level of the damping in the system.

A large number of simulated earthquake motions were used in the tests including El Centro 1940, Taft 1950, Parkfield 1966 and Pacoima Dam 1971. The natural rubber bearings reduced the forces and overturning moments to approximately one tenth of those in a conventionally fixed structure and the results demonstrated the practical possibility of this type of isolation system for full scale buildings.

ACKNOWLEDGEMENTS

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The bearings were designed and constructed by A. G. Thomas and C. J. Derham. The assistance of C. J. Derham and D. F. Tsztoo in the testing program is gratefully acknowledged.

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1. INTRODUCTION

In this report we summarize experimental findings on the use of natural rubber foundation bearings to isolate a model building from earthquake excitation. This study of the isolation system was designed to determine the suitability of the system for use in full-scale structures by investigating: (1) the behavior of the model building when on the system, (2) the stability of the model rubber bearings under large deflections, and (3) the effect of introducing large amounts of damping into the system.

The rubber bearings greatly lessened the structural response of the model building, reducing the base overturning moment of the model building to 1/10 that for the same model without rubber bearings, and base shear and interstory drift by over 80% when the El Centro 1940 N-S earthquake record was used as input to the shaking table. Similar results were obtained using the Taft 1950, Parkfield 1966 and Pacoima Dam 1971 earthquake records. When time-scaled earthquake records were used to simulate the behavior of a full-scale structure there were similar reductions in response.

In addition to establishing that the model building could be effectively isolated from earthquake-induced vibration, the study demonstrated that the natural rubber bearings, having performed well in over 65 tests, were well designed. The bearings were designed and constructed by C. J. Derham and A. G. Thomas of the Malaysian Rubber Producers Research Association, Hartford, England. The rubber bearings were linear for shear strains in excess of 100%, and were able to accept lateral deflections of three inches and more. A similarly designed full-scale rubber bearing could accommodate lateral deflections of over two feet.

Given the favorable outcome of this experimental study, further studies will concentrate on the development of complete, practical earthquake isolation systems [1]. Wind restraints in the form of mechanical fuses and energy-absorbing devices will be developed and tested. These restraints will allow a structure to behave as with a rigid foundation under service loads, wind forces and light seismic forces, but also allow the structure to become isolated under severe earthquake loading.

2. ISOLATION CONCEPT

The concept of isolation from harmful vibration is well known. Isolation has been used to reduce floor vibration induced by machinery. If the vibrating frequency of the machinery is known, the vibration in the foundation or floor can be reduced to negligible levels by providing supports for the machinery, with these supports acting as an isolation system. Buildings have also been isolated from groundborne vibration. A number of buildings have been built on isolation systems to reduce vibration caused by nearby rail and subway traffic [2]. Of the many materials used from such isolation, natural rubber has proven to be very effective.

The engineering profession has rarely attempted to extend the concept of isolation to the design of structures against earthquake vibration. No well-established criteria exist as to what constitutes an effective earthquake isolation system nor as to proper design and construction procedures. Structures on an earthquake isolation system would require, for instance, an unconventional foundation design and extensive dynamic analyses. The foundation isolation system of an isolated structure should remain stiff under wind loads, thus requiring that behavior under normal circumstances and under moderate to severe earthquake loading be differentiated.

For a structure to be isolated effectively from earthquake vibration, two criteria must be fulfilled: (1) the lowest natural frequency of an isolated structure must be well below most earthquake input frequencies, and (2) the first mode shape of an isolated structure should approach that of a single-degree-of-freedom rigid body system so that higher mode contributions will be negligible. In order to isolate a body from a particular input frequency, the frequency of the body must be less than $1/\sqrt{2}$ times the input frequency (Figure 2.1). Since most earthquake vibration is in the range 0.3 to 5.0 Hz, according to this criterion the first mode frequency of an isolated structure would be approximately 0.2 Hz. However, such a low frequency is not ideal for two reasons: (1) for a given earthquake, the lateral deflection of an isolation system of such a frequency could approach several feet, and (2) structures need not be isolated from the low-frequency components of earthquake excitations since very long-period structures typically experience low peak accelerations in their first mode. Thus, it is essential to strike a balance between reducing acceleration while minimizing displacements and for these reasons a frequency of around 0.5 Hz was thought to be a suitable compromise.

The model structure used in this study had a first mode frequency of 0.58 Hz on the rubber bearings as constructed for the isolation system. The design of rubber bearings for such an application involves a trade-off between minimizing the lateral stiffness while maintaining stability under vertical load. Reducing the lateral stiffness tends to reduce the vertical stability of the bearings. Due to the low mass of the structure, the first mode frequency could not be further reduced without sacrificing the strength of the rubber bearings. A simple analysis shows that the first mode frequency of a full-scale structure could easily be lowered to approximately 0.35 Hz. If a scale factor of 2.89 is applied to the model structure to simulate a fifty-foot tall prototype structure and an isolated rigid body mode shape is assumed, then

$$f = \frac{1}{2\pi}\sqrt{k/m} = 0.58 \text{ Hz} \qquad (1)$$

for the model structure, and

$$f = \frac{1}{2\pi}\sqrt{k(2.89)^2/m(2.89)^3} = 0.34 \text{ Hz} \qquad (2)$$

for the prototype structure.

To simulate the effect of an earthquake on the prototype structure the time scales of two recorded earthquake motions were divided by the scaling factor of 2.89 and these scaled motions were used for the loading tests on the model structure. As would be expected, the model structure was more effectively isolated from the scaled than from the unscaled earthquake inputs. Increased damping, however, had little beneficial effect when the time-scaled earthquakes were used as input ground motions.

3. ISOLATION SYSTEM

The components of the isolation system consisted of two sets of four natural rubber bearings and a set of four hydraulic shock absorbers. For one set of bearings, a low damping rubber compound (designed RL) was used, and for the other a high damping rubber compund (RH) was used. The hydraulic shock absorbers were used in conjunction with the low damping rubber bearings (together designated R-S). Only the low damping bearings were available when testing began. Until the high damping bearings could be fabricated, the use of hydraulic shock absorbers, pure viscous dampers, was the simplest way of achieving a highly damped isolation system.

The bearings used in the experimental program were similar to bearings currently used for vibration isolation in buildings located in areas of high traffic disturbance with the difference that a bearing used for earthquake isolation must have a lower lateral stiffness and be able to accept high levels of lateral deflection. Natural rubber is well suited for these purposes.

Natural rubber can accept strains on the order of several hundred percent without failure. The ultimate tensile strength of natural rubber is higher than that of any artificial rubber. The ratio of bulk modulus to shear modulus can be extremely large; for example, for soft natural rubber it can be as high as 1000, allowing the design of bearings that are very soft horizontally and very stiff vertically. Natural rubber performs well with regard to long-term performance because it creeps very little, is highly resistant to fire [3], and can be made to be effectively immune from oxidation attack. The bearings used in the experimental program were designed and constructed by the Malaysian Rubber Producers' Research Association. The low and high damping bearings were similarly constructed, the only difference being the composition of the rubber. The bearing is illustrated in Figure 3.1, its dimensions given in Figure 3.2, and the composition of the rubber for each type of bearing is provided in Table 3.1.

To provide sufficient cross-sectional area for stability under the light experimental dead load, it was necessary to develop specially low modulus rubber compounds [4]. By multilayer construction, it was possible to increase the rocking stiffness of the isolated model structure sufficiently to prevent rocking of the bearings. At the same time, the multilayer construction produced bearings that were four hundred times stiffer in the vertical than in the horizontal direction. Each laminate of rubber was 0.079 inches (2 mm) thick. Total rubber thickness in each bearing was 2.83 inches (72 mm). Table 3.2 provides the thickness of all laminates in the bearings. The lateral stiffness characteristics of the RL and RH bearings were very similar. The first natural frequency of the model structure on either set of bearings was 0.58 Hz. When the shock absorbers were added, the frequency increased to 0.60 Hz.

It was not possible to make the experimental bearings by the usual commercial process of direct chemical rubber-to-steel bonding vulcanization. They were hand fabricated from sheets of rubber vulcanization bonded to aluminum foil. The aluminum was in turn bonded to the mild steel interleaves using industrial quality double-sided adhesive tape over two-thirds of the surface area, and epoxy resin for greater shear strength over the remaining one-third area. The bearings so-fabricated were adequately strong for the tests described in this report, being capable of sustaining repeated shear deformation in excess of 100%, but were clearly not as strong nor as durable as equivalent commercially produced bearings would be. Due to the controlled conditions of the tests, fire or oxidation attack was not considered. The theoretical vertical stiffness of these bearings was approximately 500,000 lbs-per-inch. Due to the 72 layers of adhesive tape, the measured effective vertical stiffness at the working load was on the order of 150,000 lbs-per-inch.

The vertical stiffness characteristics of the low damping bearings are shown in Figure 3.3. The vertical stiffness characteristics of the high damping bearings were similar. The pronounced soft lead-in is primarily the result of the method of construction and would not normally be so marked. In a static load test, the bearings were vertically cycled from 5,000 to 20,000 pounds. The bearings displayed almost no hysteresis after the first soft lead-in cycle. The slight amount of creep resulted from creep of the adhesive tape. After three cycles, no discernible creep occurred. The ultimate vertical strength of each bearing was 30,000 lbs, three times the static dead load on them due to the weight of the model structure.

The horizontal stiffness characteristics of the low and high damping rubber bearings are shown in Figure 3.4. The data are taken from the dynamic earthquake simulator tests. The hysteresis loops represent approximately 3 and 10% critical damping. The response of the rubber bearings was essentially linear to shear strains in excess of 100%. The dynamic stiffness was about 320 to 360 lbs-per-inch, and the static horizontal stiffness of individual bearings was measured to be between 360 and 400 lbs-per-inch. Thus, the stiffness of the bearings is essentially frequency independent.

4. EXPERIMENTAL MODEL AND TESTING FACILITY

The experimental work was carried out using the twenty by twenty foot shaking table at the Earthquake Engineering Center of the University of California, Berkeley. The shaking table is described in Reference [5]. The model steel frame building is illustrated in Figures 4.1 and 4.2. The model weighed 39,500 pounds and was twenty feet tall. More detail on this model and the data reduction process is provided in References [1, 6 and 7]. Figures 4.3 and 4.4 illustrate the mounting of the model on the rubber bearings. The heavy W10x49 base floor girders ensured that the rubber bearings would undergo little bending deformation, with the isolation devices when used placed beneath each of the column legs.

Fifty-eight transducers were used to collect data. The data were scanned at approximately 50 samples per channel per second.

The span number preceding the specified earthquakes in this text refer to the intensity of the input motion. A span 1000 input motion corresponds to a peak displacement of ± 5 inches; the peak displacement at a lower span number is reduced in proportion.

5. EXPERIMENTAL TEST PROGRAM AND DATA REDUCTION

Four foundation conditions were tested on the earthquake simulator table: (1) with the foundation conventionally bolted and incorporating no isolation device (referred to as FIX), (2) with the low damping rubber bearings installed (RL), (3) with the high damping rubber bearings installed (RH), and (4) with the low damping rubber bearings and shock absorbers installed together (R-S). The building model was the same for all four foundation conditions. For each foundation condition as many as four horizontal and two vertical earthquake simulation tests were performed. In Table 5.1 the peak displacements and accelerations of the input motions referred to in this report are given. Comparisons between tests as well as detailed discussions of selected individual tests are presented in the following sections.

For purposes of data reduction, the long direction of the model structure was defined as the North-South direction. The shaking table motion was in the N-S and vertical directions only. Positive results represent response to the North.

<u>Response Spectra</u> - Each response spectrum calculated at 1, 3, 10, and 15% damping ratio.

<u>Table Displacement and Acceleration</u> - Actual recorded table motions during testing.

<u>Rubber Pad Displacement Relative to Table</u> - The two nearly identical traces plotted, solid and dashed, represent, respectively, the lateral deflections of the rubber bearings on the west and east longitudinal frames (A and B) of the model. Discrepancies between these traces would indicate torsional response of the structure. Other dashed traces refer to comparative data.

1st, 2nd, and 3rd Floor Displacement Relative to Table - These data were obtained by subtracting the recorded table displacement from the absolute motion of each floor.

Base, 1st, 2nd, and 3rd Floor Absolute Acceleration - Recorded accelerations of the concrete blocks on each floor.

Base, 1st, 2nd and 3rd Floor Shear and Overturning Moment - The first story shear represents the summation of the first, second, and third story inertia forces. The inertia forces were calculated from the measured floor accelerations. The floor overturning moments are the summation of the floor inertia forces about the floor level in consideration. Base shears and overturning moment do not apply to the fixed foundation model.

NA - NB and SA - SB Transverse Displacement - These data are the transverse displacements along column lines NA - NB and SA - SB, and were reduced from the square of the potentiometer gage displacement data in the EW direction less the square of the potentiometer data in the NS direction. The error due to this linear approximation is less than 1%.

Absolute and Relative Vertical Acceleration - The accelerations are measured at the base of the column legs, directly above the rubber bearings. Relative acceleration is the absolute minus the acceleration of the table.

All tests using a particular earthquake input, regardless of span setting or base fixity, have been shifted in time so that peak table displacement occurs at the same instant. This is to facilitate comparison between tests.

6. RESULTS

Selected test results are discussed below. For each of the four foundation conditions, the results of one or two tests are discussed in abbreviated form. For the El Centro tests on the low damping rubber bearing foundation, a comprehensive set of figures is provided. The complete test data for other input motions indicated that the response to the El Centro motion was typical, and thus will not be discussed in detail.

Figures 7.1 and 7.2 show the response spectra for the El Centro and time-scaled El Centro input motions. The first natural period of the structure was approximately 1.7 seconds (see Table 7.1), thus putting the model at the lower end of the acceleration spectrum of the El Centro motion, but well within the magnified portion of the displacement spectrum. However, for the time-scaled El Centro motion, the natural period of the model is in the portion of the displacement spectrum where peak response displacement is close to the maximum ground displacement. It cannot be assumed that this is typical; it would be unwise to design prototype bearings only for maximum expected ground displacement.

For tests of the fixed base structure using the El Centro 450 and Parkfield 200 motions, the structure had a period of approximately 0.50 seconds and a damping ratio of less than 1%. Third floor accelerations were amplified by about 400% from the input ground acceleration (Figures 7.3 and 7.4). Although not shown in the figures, the maximum first story drift to the El Centro motion was 1.4 inches, or 1.7% of first story height. A great deal of damage to partitions would have occurred in an actual structure to even this medium sized earthquake.

For the rubber bearing isolated structure subjected to the El Centro 450 motion, peak third floor acceleration was only 33% of the maximum input ground motion acceleration (Figures 7.5 and 7.6). The maximum first story drift was correspondingly small, less than 0.1 inches or 0.12% of first story height. For this case, little or no damage to partitions would be expected.

The solid and dashed lines in the rubber pad displacement traces (Figure 7.5) are almost identical, indicating that no significant torsion occurred despite slight differences in the stiffness of the four rubber bearings. This was typical of tests on the isolated model.

The floor accelerations (Figure 7.6) indicate a slight second mode response at approximately 3.8 Hz, also evident in other tests. When vertical input motion was considered, a third mode lateral response was induced (Figure 7.14). It is not known why the third mode response occurred. This third mode did not correspond to a rocking mode. In any event, the influence of second, third, and higher mode responses on the behavior of the isolated model was visible only in acceleration traces and was always very small.

Due to the interstory stiffness proportions of the model, the higher shear mode contributions for the El Centro 450 input motion completely cancelled out at the base (Figure 7.7 and 7.8). For taller buildings, in which interstory stiffness decreases with height, the higher mode shear contributions would not necessarily cancel out at the base. Shears and overturning moments differed by a factor of approximately eight for the fixed and isolated systems. (Figure 7.24).

Some transverse and torsional motion was induced in the isolated model during the El Centro 450 motion test (Figure 7.9). The transverse rigid body displacements had a period of approximately 1.8 seconds, indicating that the stiffness characteristics of the rubber bearings were isotropic in both horizontal directions. The rotational inertia of the building, calculated assuming the model to be a rigid body, resulted in the analytical calculation of the torsion mode period to be 1.0 seconds. This was a good assumption, as the experimentally observed torsion mode period was 0.95 seconds.

The response of the model on the low and high damping rubber bearings to the El Centro 400 input motion is indicated by the solid and dashed lines, respectively, in Figure 7.10. During the first 6.5 seconds of the El Centro motion, the response of the low and high damping bearings differed little, principally because building response during such strong motion portions of earthquake records is due to forced vibration. After 6.5 seconds, the input motion decreased and the structure began to respond in free vibration. Linear increases in input motion produced proportional linear increases in peak displacement, as indicated in Table 7.2.

The response of the model structure to the vertical motion was a simple rigid body vertical mode between 10 and 12 Hz. By coincidence, the vertical frequencies of vibration for the four floor beams were between 12 and 15 Hz. The close tuning between these vertical modes made it impossible to obtain an exact definition of the vertical behavior of the model by resonance testing. However, no interaction between these tuned vertical vibration modes was observed under the earthquake excitation. The relative acceleration data in Figure 7.12 do, however, indicate that the vertical frequency of the model was in the range 11 to 13 Hz.

For the El Centro 400 horizontal and 350 vertical input ground motion, peak vertical table acceleration was .267g while the vertical acceleration of the model was .324g. For the Pacoima Dam 200 horizontal and 100 vertical input motions corresponding values were .102 and .112g.

The important points about the vertical response of the structure are thus: there was almost no amplification of the vertical signal into the structure; there were no discernible rocking or up-and-down motions; and no rubber bearings ever uplifted enough to go into tension.

When vertical as well as horizontal input motion was considered, there was no significant difference in the horizontal displacement of the model (Figure 7.13). Although second and third mode horizontal responses were excited (Figure 7.14), these higher mode accelerations were in no case greater than 0.05g. A third mode high-frequency acceleration between 6.5 and 9 seconds into the Taft motion was caused by slippage of a bolt (Figure 7.15). The model was particularly sensitive to the Parkfield motion (Figure 7.16) due to the sinewave shape of the input displacement at the natural period of the model.

For the time-scaled input motions, both the fixed and low damping rubber bearing foundation model responses included a strong second mode contribution (Figures 7.17 and 7.18). While higher mode accelerations were greater than the first mode acceleration for the low damping bearing foundation, they were still less than one-sixth peak input ground acceleration. When higher damping was used, the peak displacement of the model structure slightly increased (Table 7.2). Figures 7.21 through 7.26 corroborate the preceding observations.

7. CONCLUSIONS

The major differences between the response of the fixed foundation model and that of the model with natural rubber bearings installed in the four-story steel frame were: (1) that the isolated structure experienced far lower shears, accelerations, and overturning moments, and (2) that the isolated structure underwent large rigid body translations. The large translations necessary for a base isolation system to be effective were easily attained through the use of specially constructed natural rubber bearings that were capable of undergoing repeated deformation of over 3 inches without deterioration.

For unscaled earthquake motions, peak displacements were reduced by 20-30% when damping was increased from 3 to 10%. For time-scaled motions, however, increased damping had little effect on structural response. For scaled and unscaled motions, increased damping reduced the number of large displacement cycles. Response was calculated for a prototype structure, with analyses indicating that increased damping would be most beneficial for unusually long period strong intensity earthquakes. The tests showed that the most obvious tradeoff for increased damping in the rubber formulations was an increased tendency of the bearings to creep. This problem ought not to arise, however, when full-scale high damping bearings are used.

The very stiff vertical characteristics of the rubber bearings satisfactorily reduced rocking and vertical response of the structure. Overall, the simple earthquake isolation system described in this report isolated the model structure to a high degree from the damaging effects of the earthquake ground motion inputs used in the testing program. Still to be developed is a method of accommodating service and wind loads and the large displacements that occur at the base of the sturcture. Work has already begun on developing an effective energy-absorbing device or steel fuse to be used in conjunction with the natural rubber bearings. The system described herein could, with only minor detailing to limit maximum displacements, be adapted to provide earthquake protection for special structures such as nuclear power plants. The possibility of using base isolation for nuclear power plants has been discussed by Skinner, et al. [8].

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	Low Damping	High Damping
OENR A 75/25	100	100
Zinc Oxide	3	
Stearic Acid	2	
SRF Black		30
Antidegradant[1]	1	
Antioxidant[2]		1
CBS	0.34	
Sulphur	1.40	
Dicumyl Peroxide		1
Cure Time at Temperature	40 min 140°C	50 min 160°C

Notes

1. N-Isopropyl-N'-phenyl-p-phenylenediamine, Nonox ZA, now Permanax IPPD (Vulnax International Ltd).
2. 2,2'-Methylenebis-(4-methyl-6-t-butylphenol), Antioxidant 2246 (Anchor Chemical Co).

TABLE 3.1. Formulations For The Rubber Bearings

LAMINATE	NUMBER OF LAYERS	THICKNESS, EACH LAYER (inch)	TOTAL THICKNESS (inch)
Rubber Sheets	36	.079±	2.83±
Mild Steel Inner Plates	30	.0625	1.88
Mild Steel Exterior Plates	12	.0625	0.75
Aluminum Foil and Adhesive Tape	72	.01±	0.72±
TOTAL THICKNESS, UNLOADED STATE =			6.25 inch

Table 3.2. Thickness of Rubber Bearing Laminates

EARTHQUAKE	SPAN	DISPLACEMENT Max. (inch)	DISPLACEMENT Min. (inch)	ACCELERATION Max. (inch)	ACCELERATION Min. (inch)
EL CENTRO	400 450	2.17 2.33	-1.70 -1.76	.241 .251	-.292 -.310
EL CENTRO Vertical	350	0.87	-1.12	.257	-.156
EL CENTRO Time Scaled	120	0.56	-0.59	.500	-.635
PARKFIELD	200	0.93	-0.52	.034	-.092
PARKFIELD Time Scaled	280	1.46	-1.13	.852	-1.23
TAFT	350	1.76	-1.15	.203	-.188
PACOIMA DAM	200	1.09	-0.94	.245	-.261
PACOIMA DAM Vertical	100	0.26	-0.26	.102	-.083

Table 5.1. Input Earthquake Records

	FIX FOUNDATION 4 Floor Model		RUBBER FOUNDATION 4 Floor Model		
	1ST Mode	2ND Mode	1ST Mode	2ND Mode	3RD Mode
FREQUENCY	2.05 Hz	7.33 Hz	0.58 Hz	3.84 Hz	8.89 Hz
MODE SHAPE					
3RD Floor	1.00	1.00	1.00	1.00	1.00
2ND Floor	0.73	-0.25	0.98	0.42	-0.85
1ST Floor	0.46	-1.00	0.96	-0.33	-1.10
Base Floor	--	--	0.92	-1.02	0.88

Table 7.1. Frequencies and Mode Shapes for FIX and RL Foundations

	TABLE	MOTION	LOW DAMPING (RL)		LOW DAMPING + SHOCK ABSORBER (R-S)		RL vs. R-S
EARTHQUAKE	MAX. TABLE ACCL. (G)	MAX. TABLE DISP. (INCH)	MAX. 3RD Floor Accl. (G)	MAX. RUBBER DISP. (INCH)	MAX. 3RD Floor Accl. (G)	MAX. RUBBER DISP. (INCH)	Δ% DISP.
EL CENTRO 100	.072	.528	.033	.707	.036	.542	-23.3%
200	.137	1.052	.064	1.401	.065	1.102	-21.3%
300	.204	1.582	.089	2.144	.082	1.755	-18.2%
400	.278	2.112	.110	3.016	.113	2.418	-19.8%
450	.310	2.377	.122	3.243	.126	2.774	-14.5%
PARKFIELD 200	.092	.931	.073	1.839	.063	1.310	-37%
TAFT 350	.202	1.761	.220	3.070	.102	2.281	-34.5%
PACOIMA DAM 200	.261	1.09	.106	1.08	--	--	--
EL CENTRO Time Scaled 60	.299	.286	.046	.569	.062	.524	- 7.9%
120	.634	.539	.100	1.149	.118	1.076	- 6.4%
PARKFIELD Time Scaled 120	.437	.630	.066	.893	.093	.906	+ .9%
180	.685	.943	.085	1.356	.119	1.372	+ 1.2%
280	1.226	1.460	.143	2.139	.171	2.165	+ 1.2%

Table 7.2. Effect of Increased Damping on Maximum Rubber Bearing Displacements and Accelerations

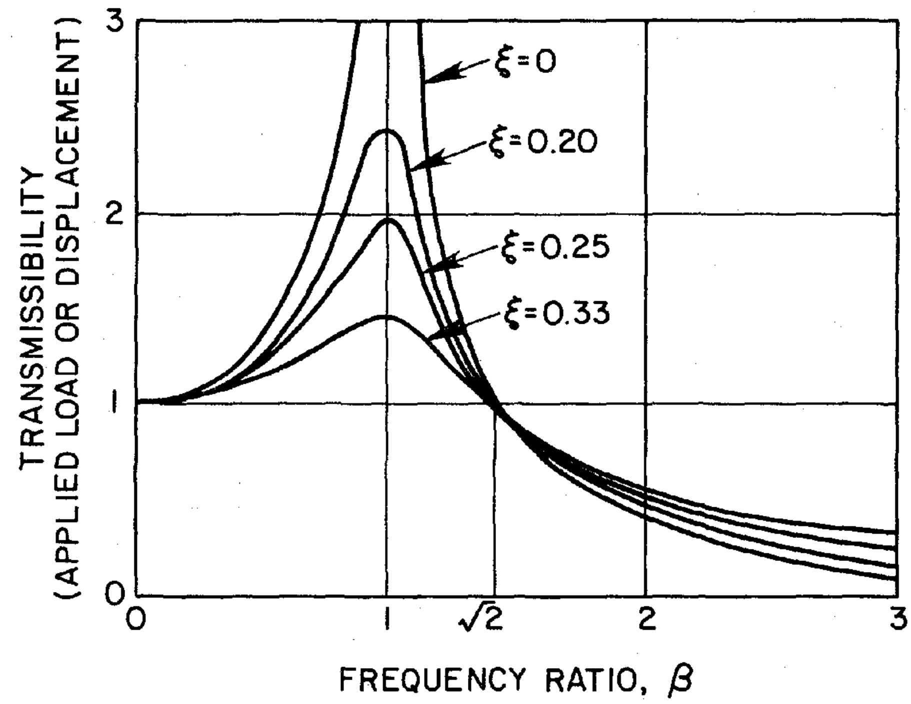


FIGURE 2.1. Vibration-Transmissibility Ratio

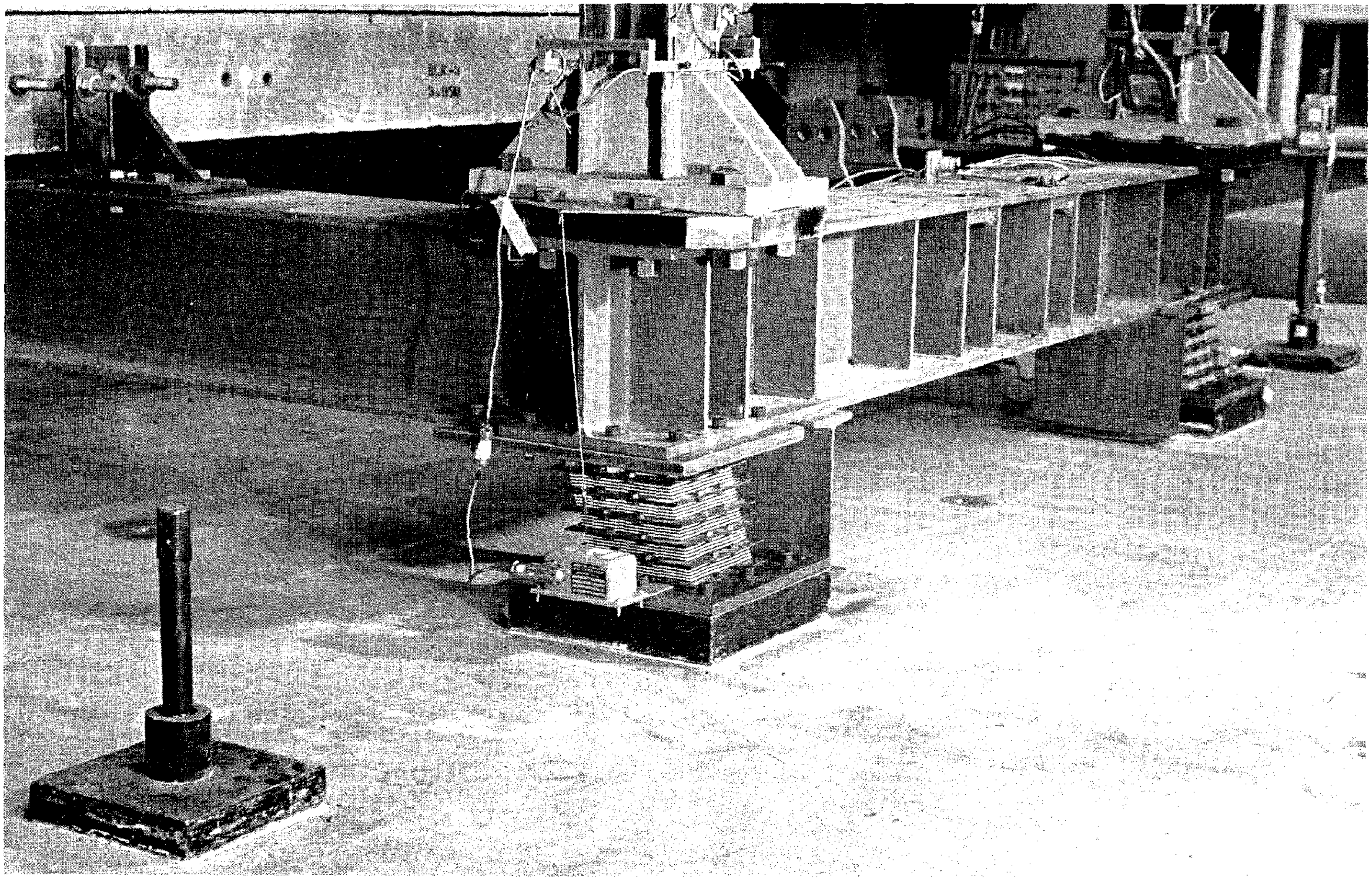


Figure 3.1. Shear Deflection of Rubber Bearings

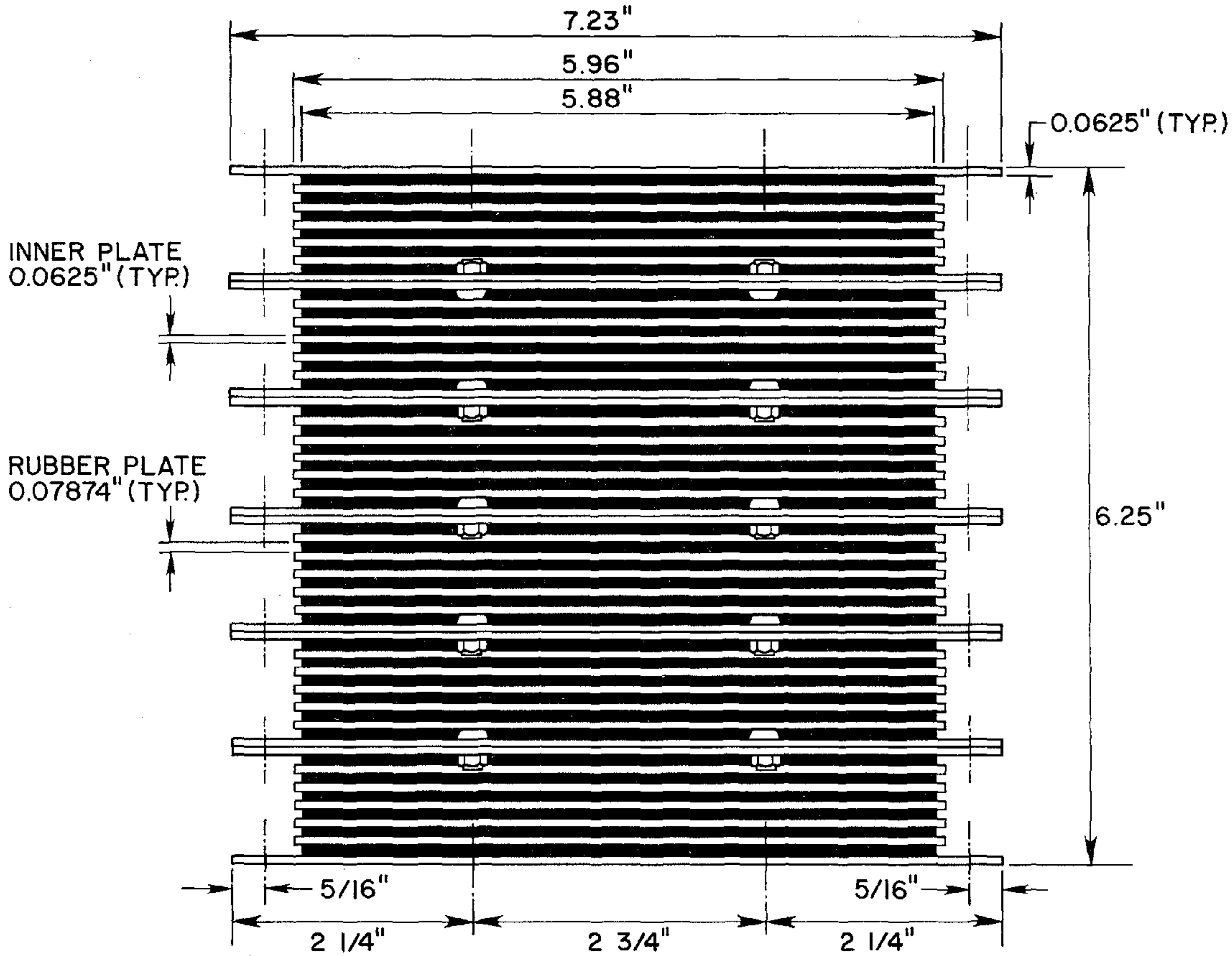


Figure 3.2. Dimensions of Natural Rubber Bearings

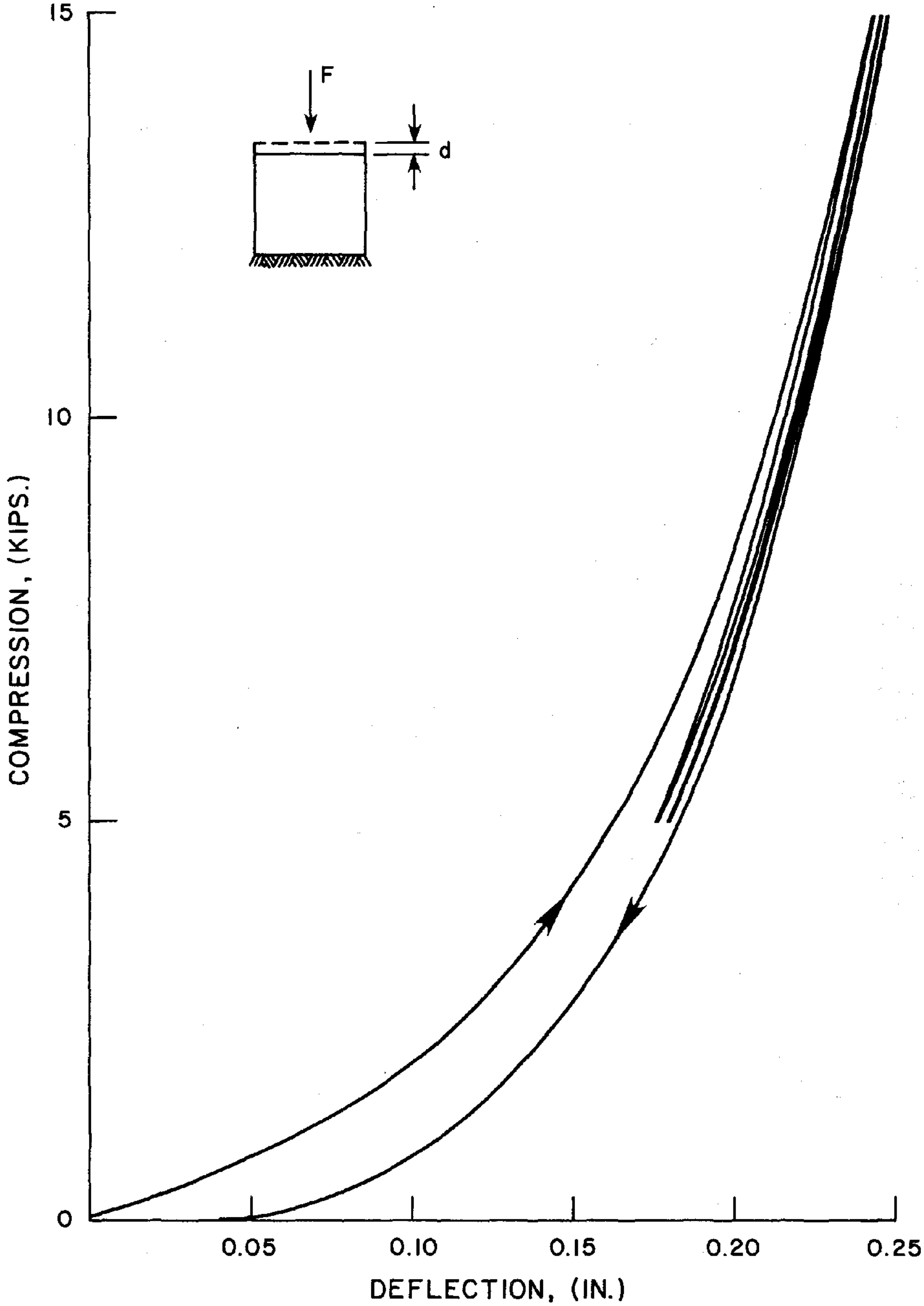


Figure 3.3. Vertical Stiffness Characteristics of Low Damping Rubber Bearings

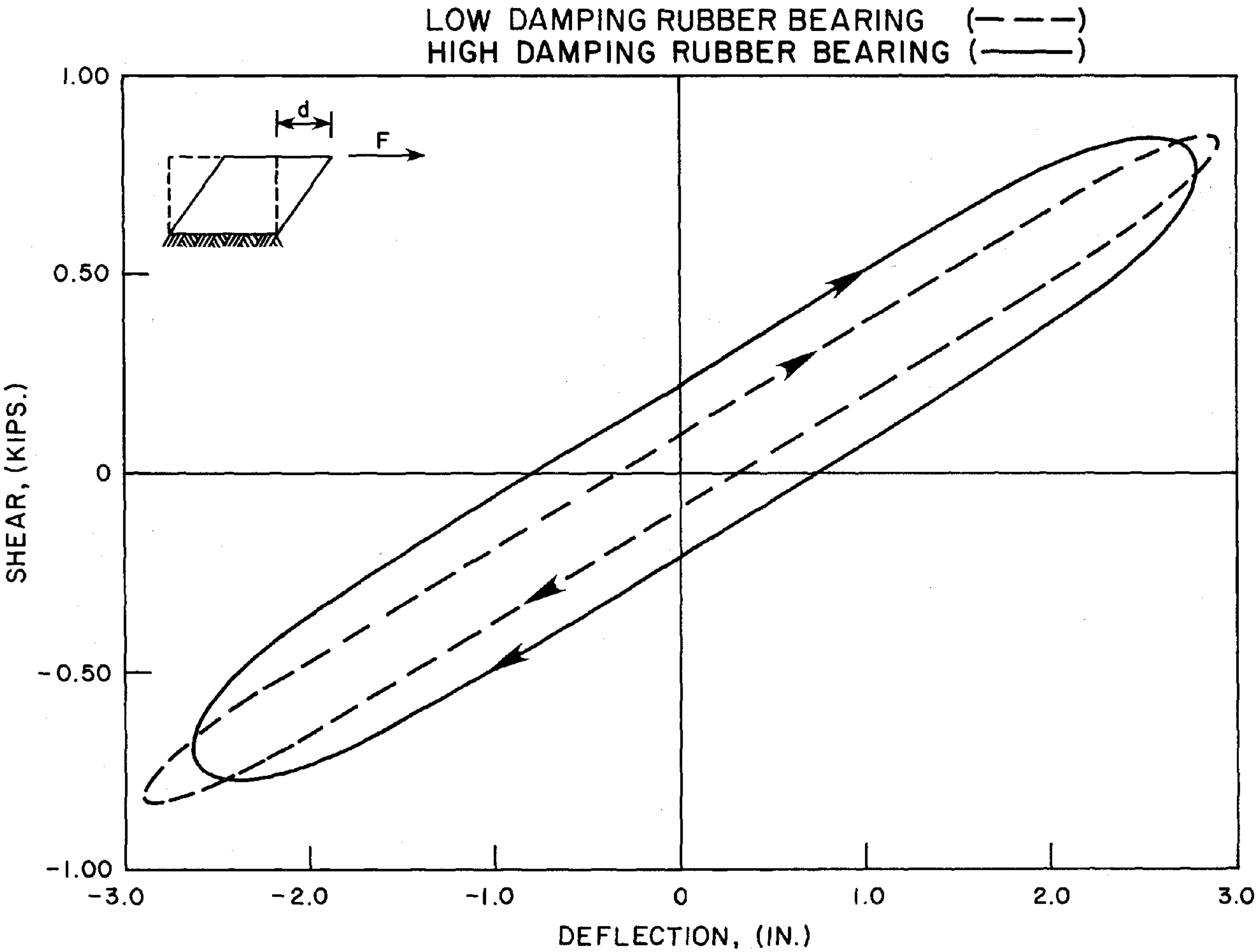


Figure 3.4. Horizontal Stiffness Characteristics of Low and High Damping Rubber Bearings

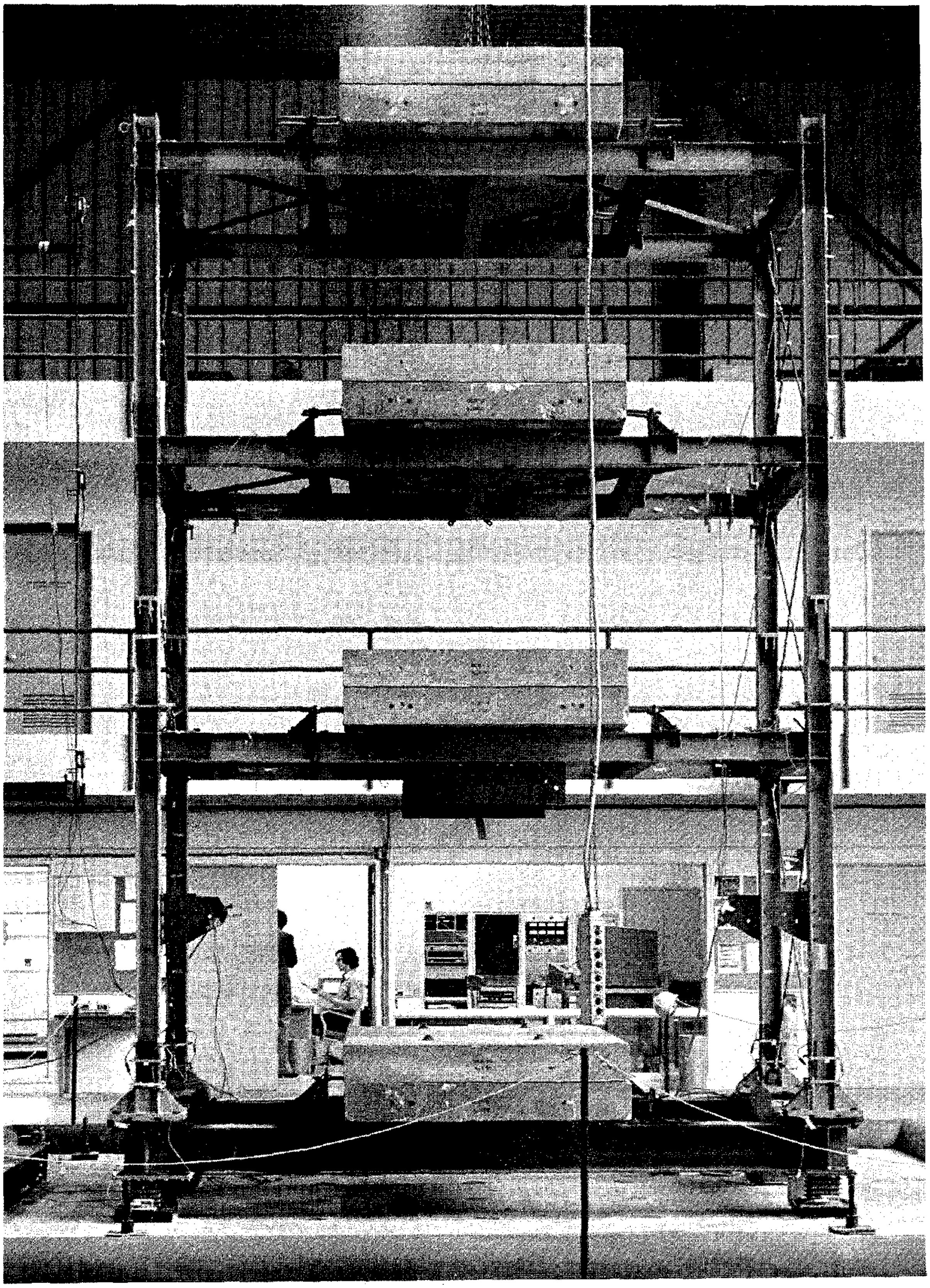


Figure 4.1. Model Structure

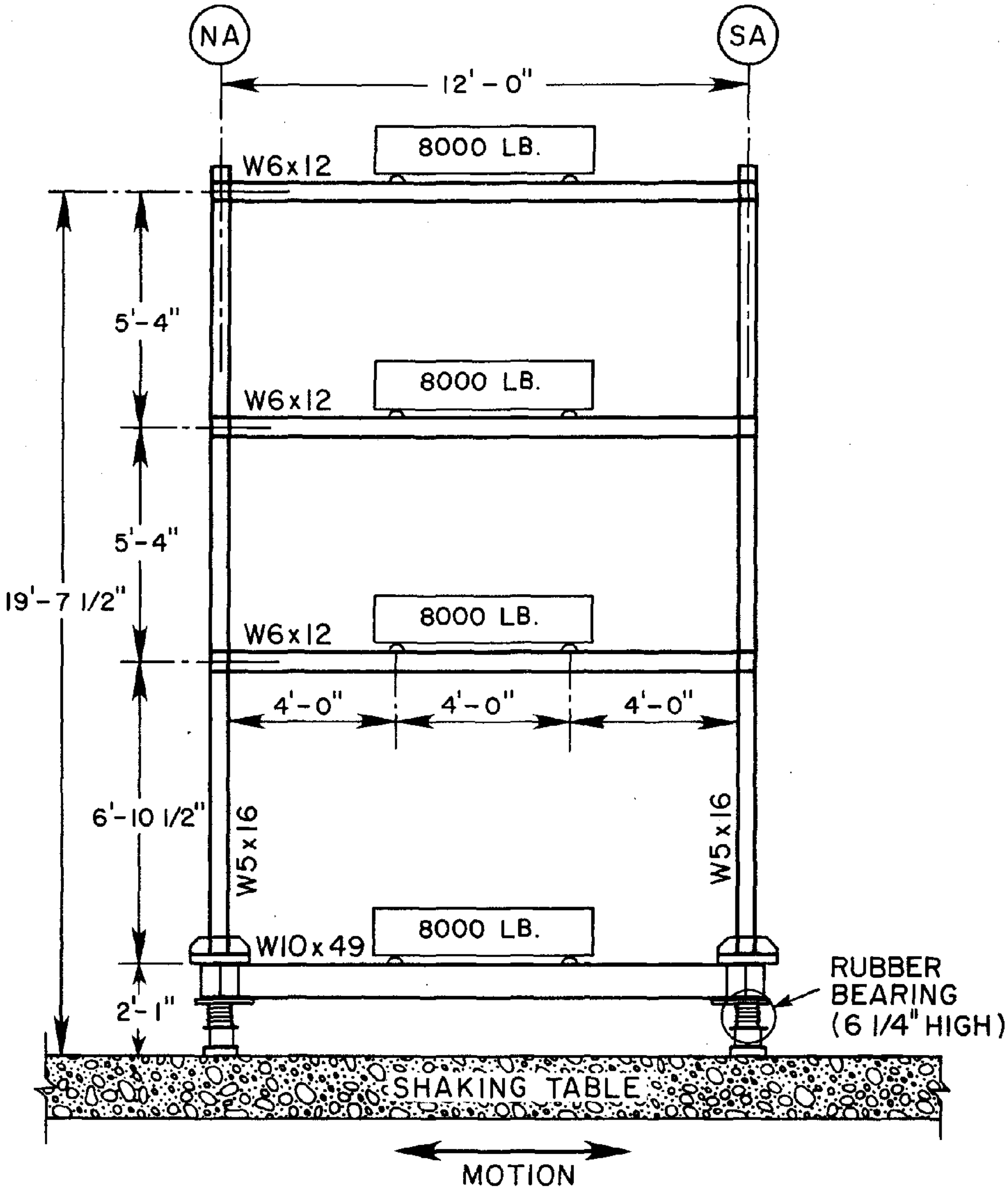


Figure 4.2. Dimensions of Structure

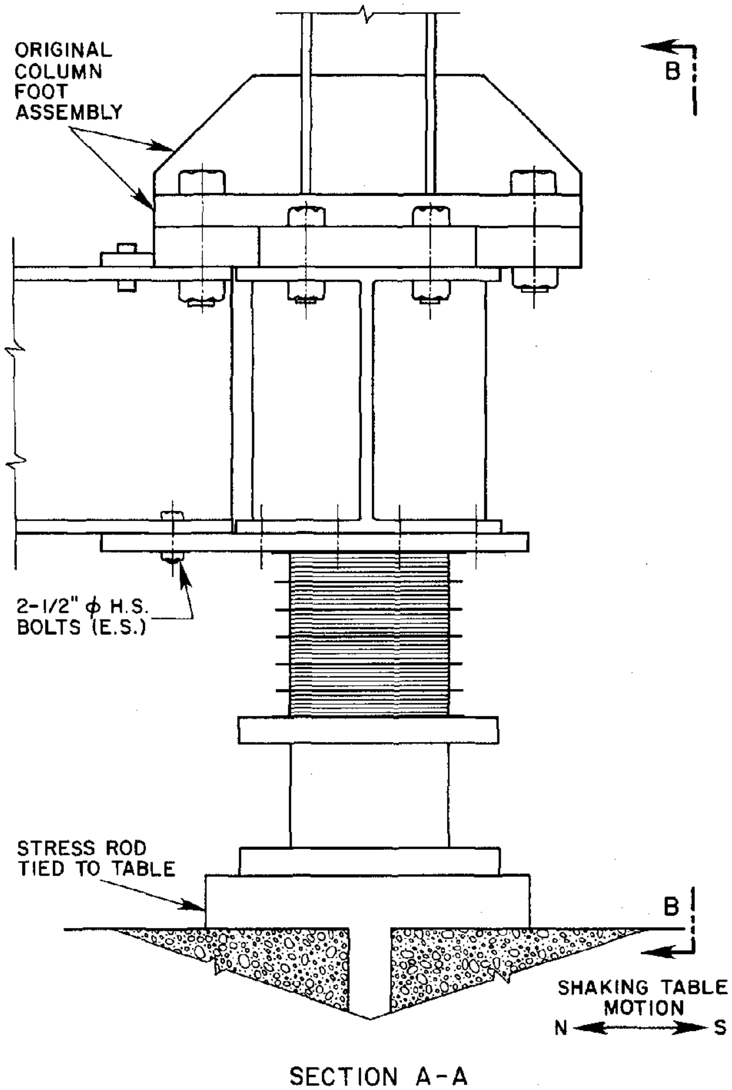


Figure 4.3. Rubber Bearing Connection - Detail

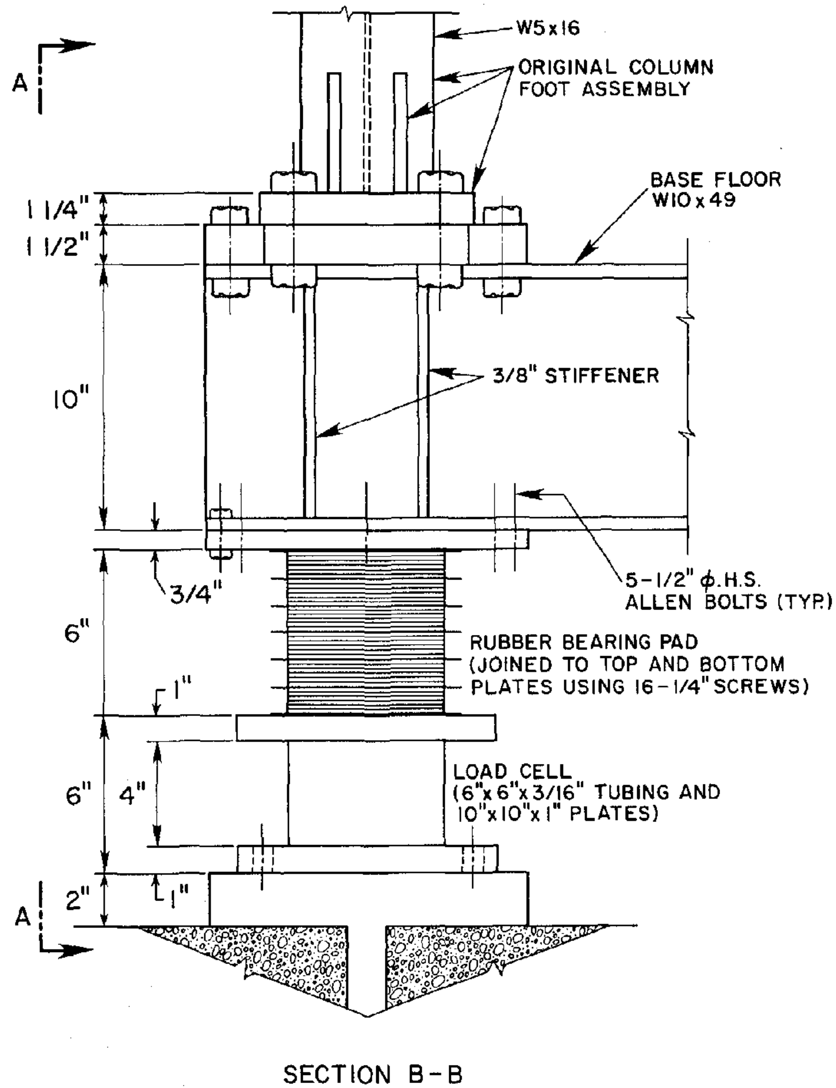


Figure 4.4. Rubber Bearing Connection - Detail

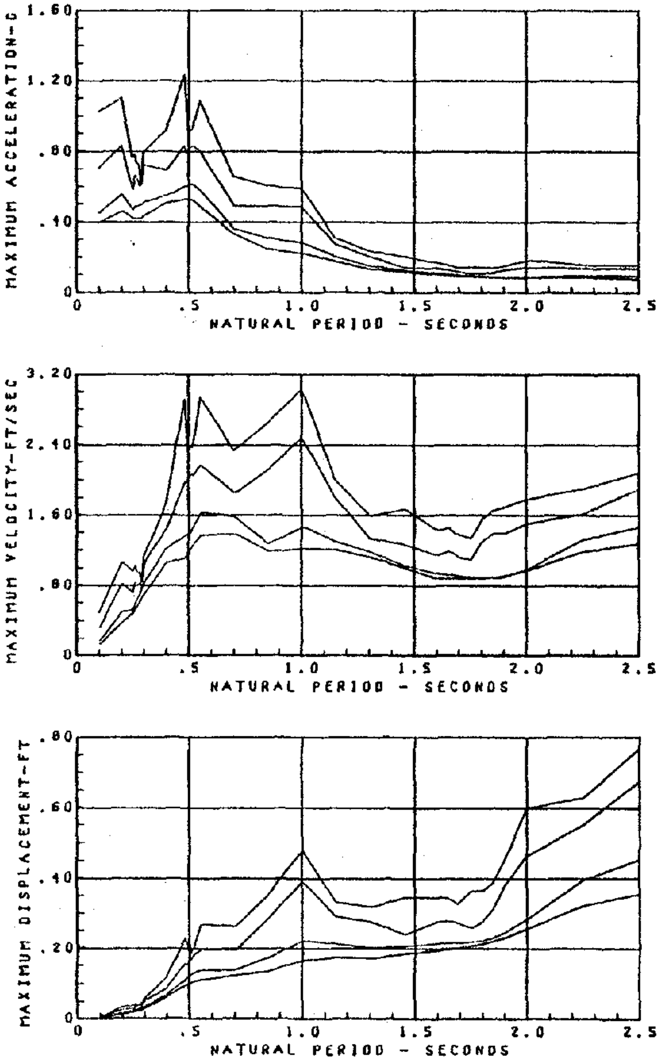


Figure 7.1. Response Spectra - El Centro 450

ξ = 1,3,10 and 15%

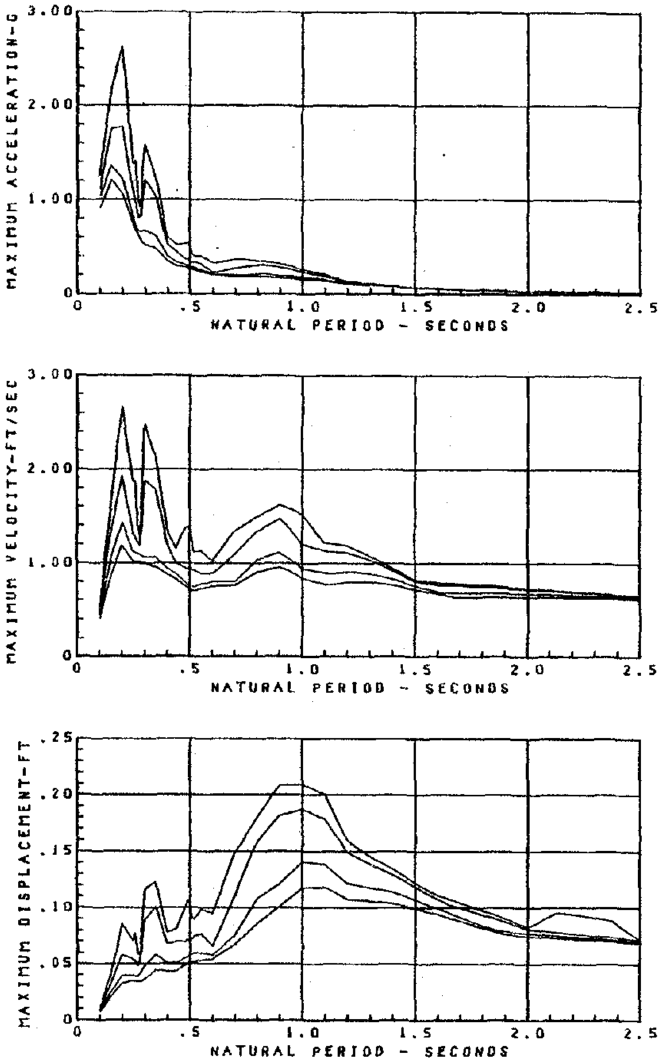


Figure 7.2. Response Spectra - El Centro 120, Time Scaled

ξ = 1, 3, 10 and 15%

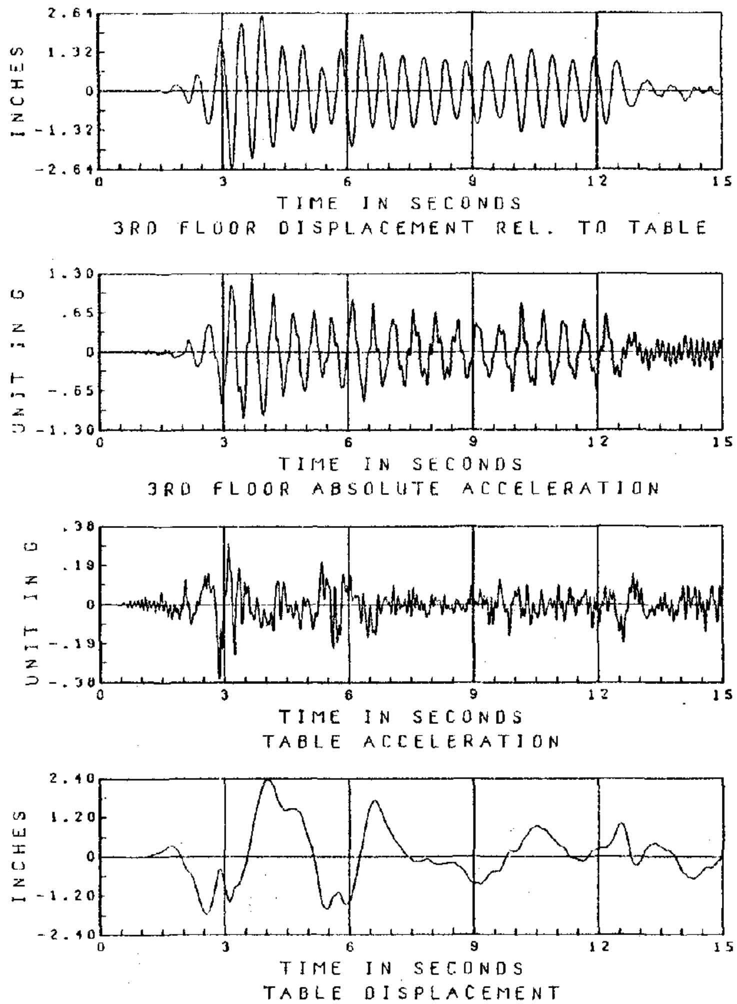


Figure 7.3. Fix Base, General Response, El Centro 450

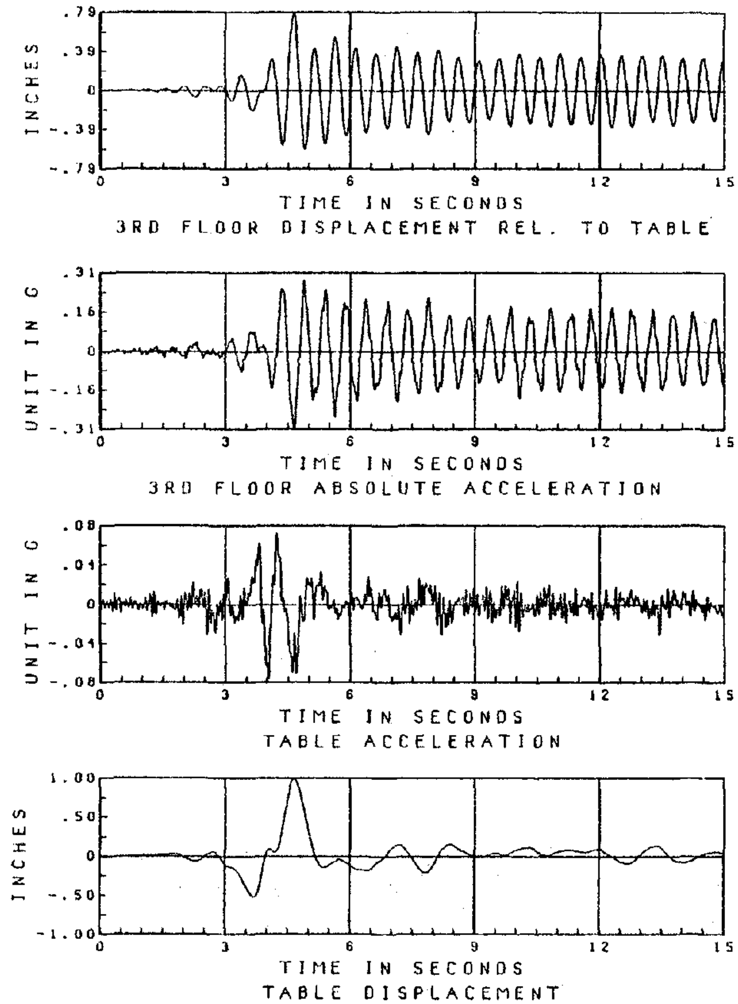


Figure 7.4. Fix Base, General Response, Parkfield 200

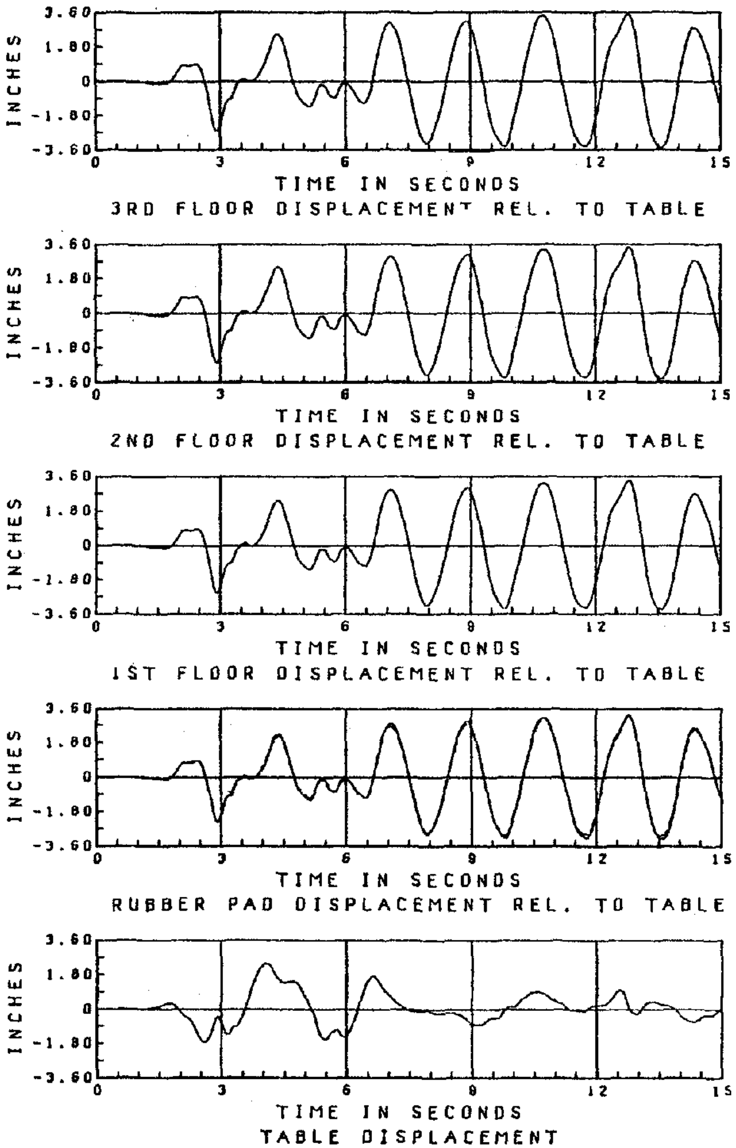


Figure 7.5. RL Base, Displacements, El Centro 450

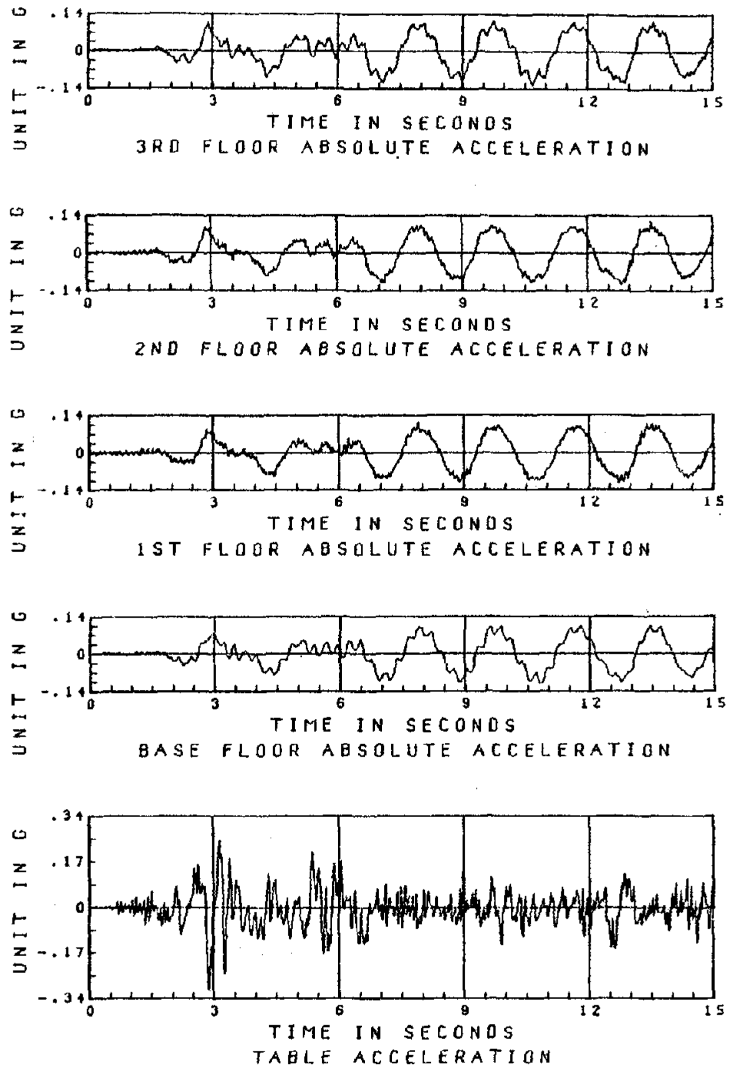


Figure 7.6. RL Base, Accelerations, El Centro 450

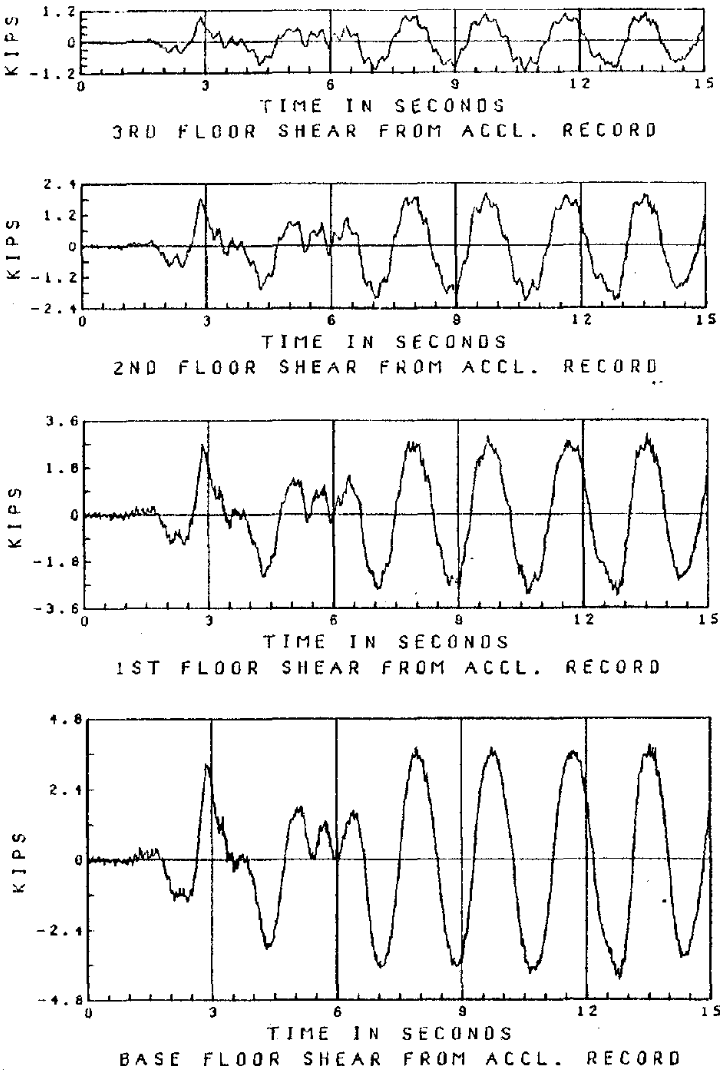


Figure 7.7. RL Base, Floor Shears, El Centro 450

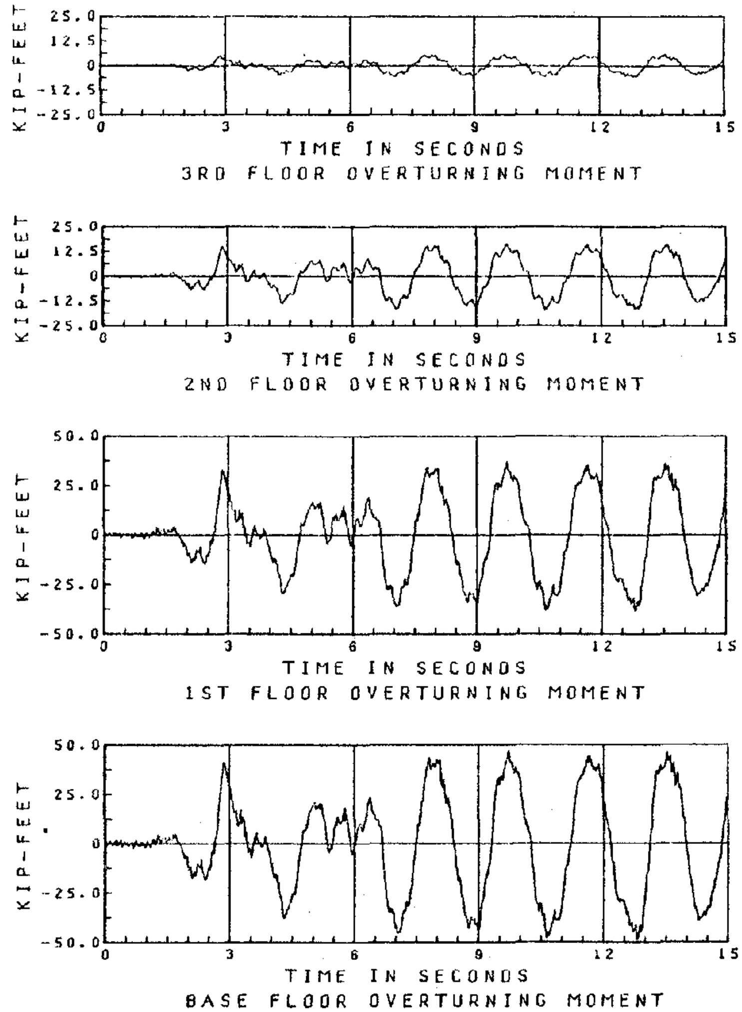


Figure 7.8. RL Base, Overturning Moments, El Centro 450

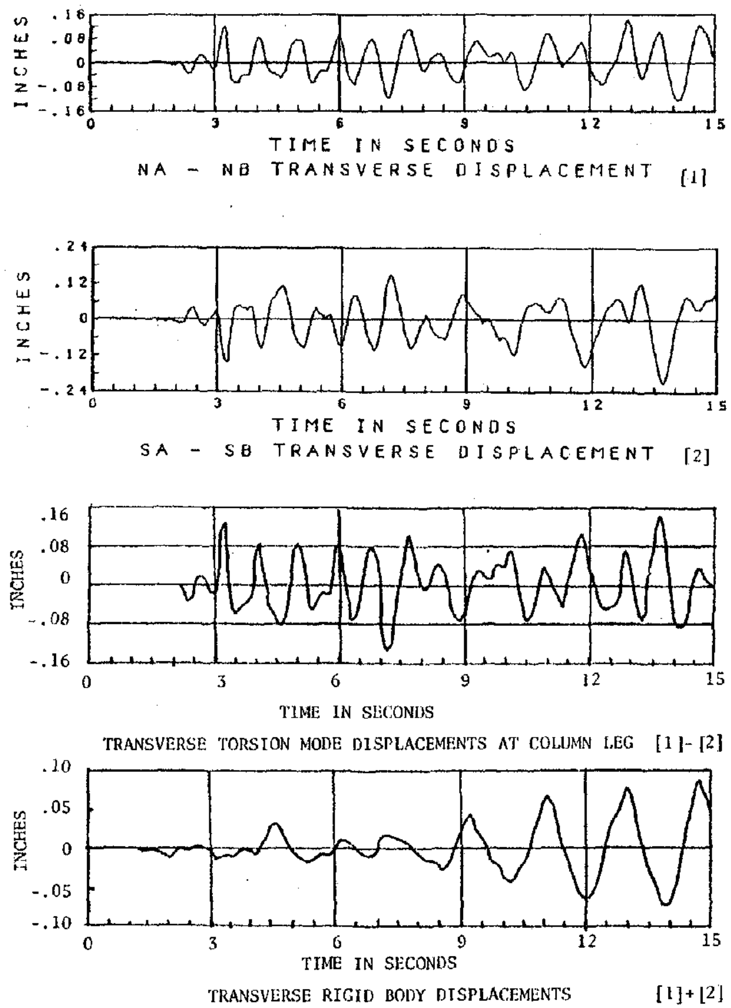


Figure 7.9. RL Base, Transverse Motions, El Centro 450

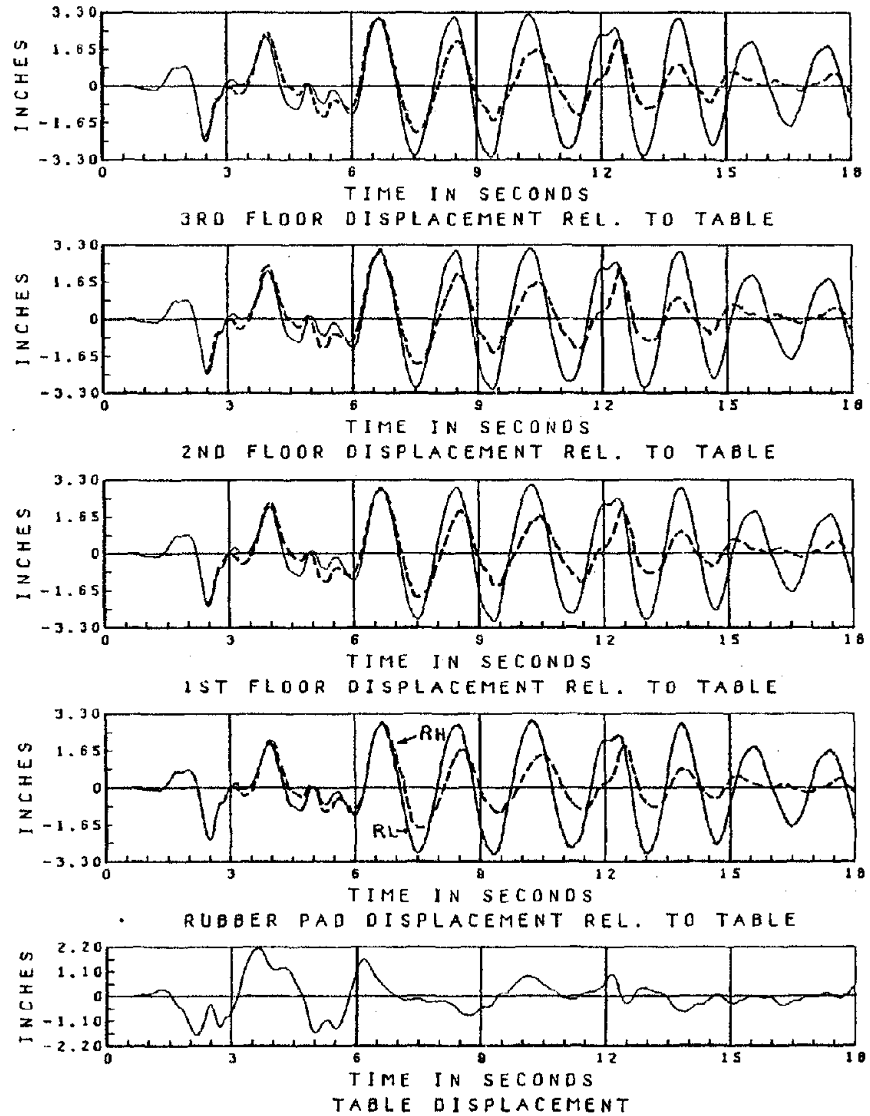


Figure 7.10. RL + RH Bases, Displacements, El Centro 400

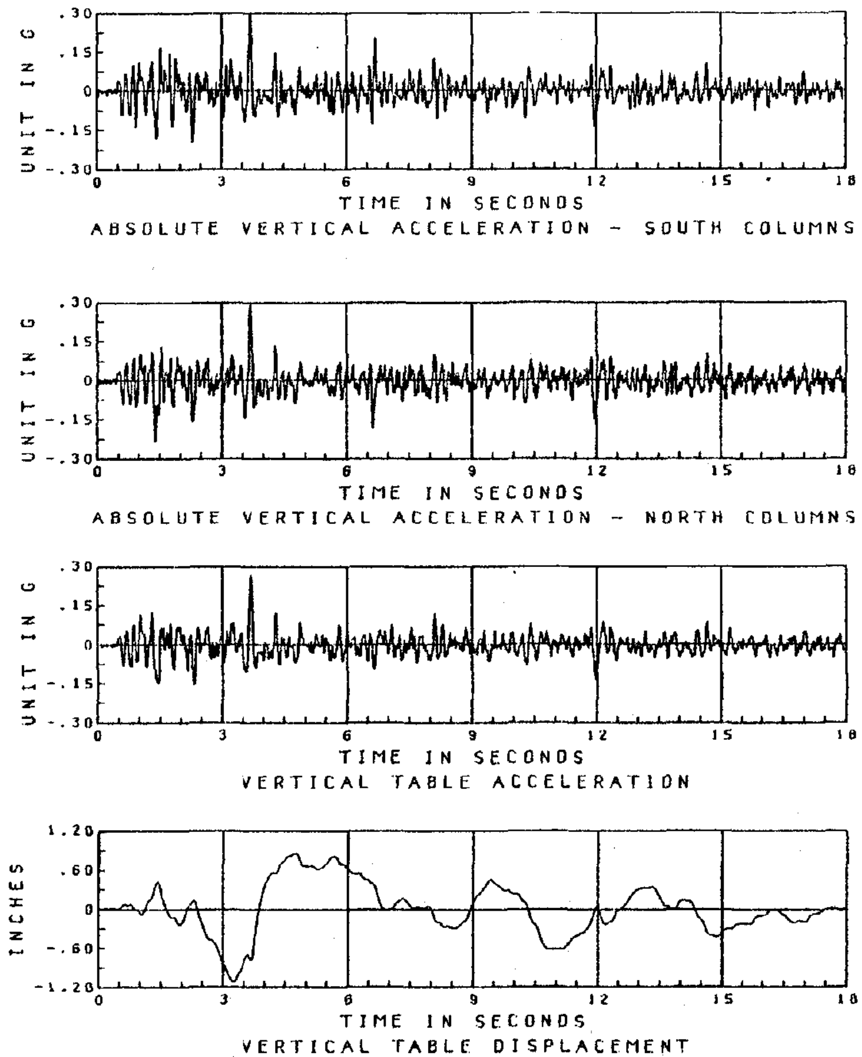


Figure 7.11. RL Base, Absolute Vertical Accelerations,

El Centro 400 Horizontal, 350 Vertical

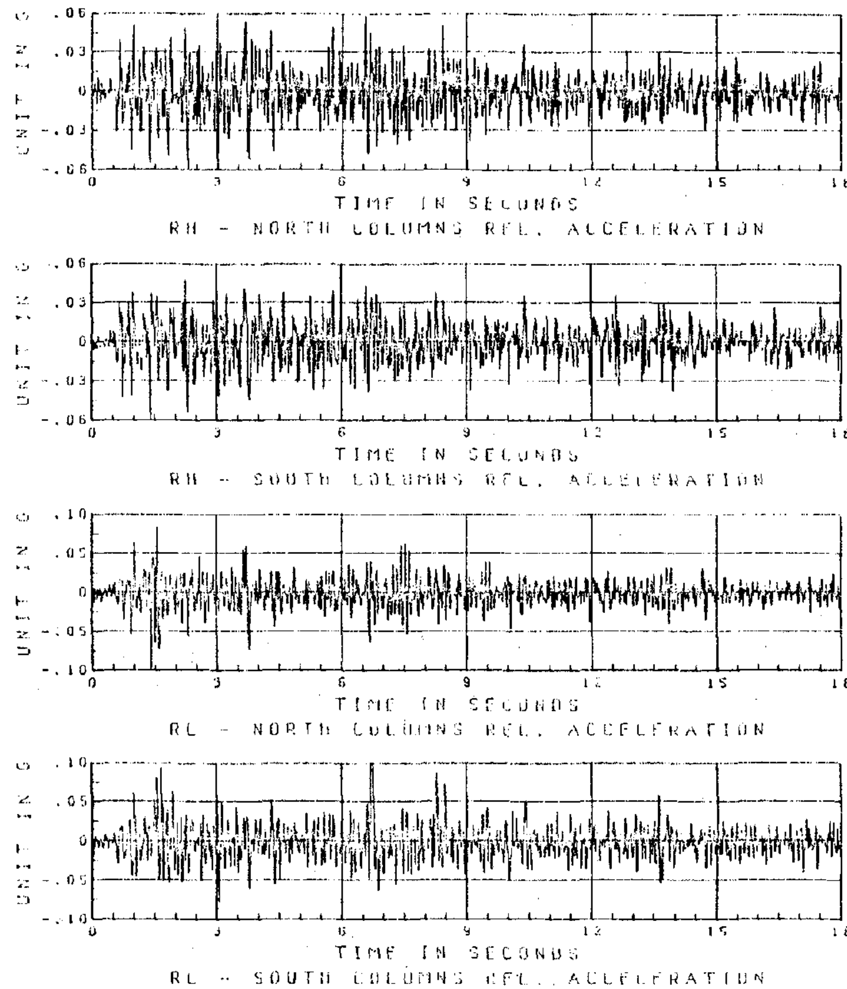


Figure 7.12. RL + RH Bases, Relative Vertical Accelerations,

El Centro 400 Horizontal, 350 Vertical

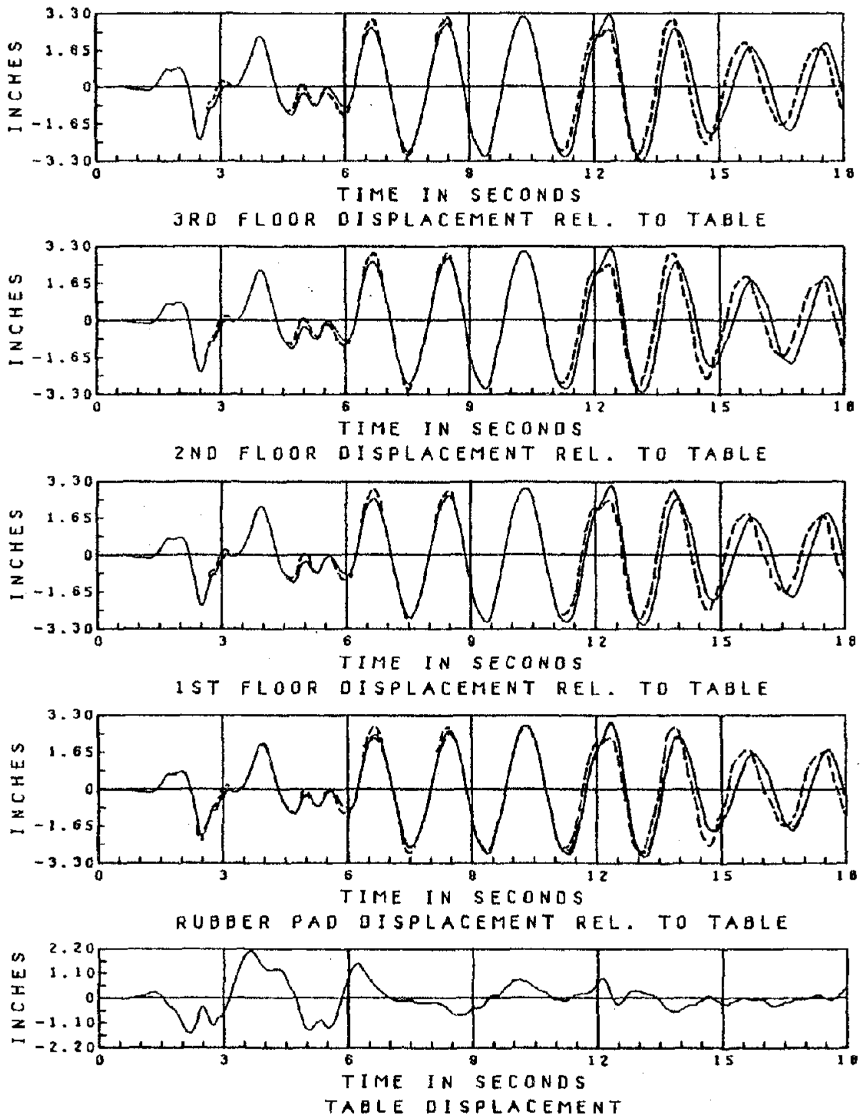


Figure 7.13. RL Base, Displacements with (——) and without (---)

Vertical Motion, El Centro 400 Horizontal, 350 Vertical

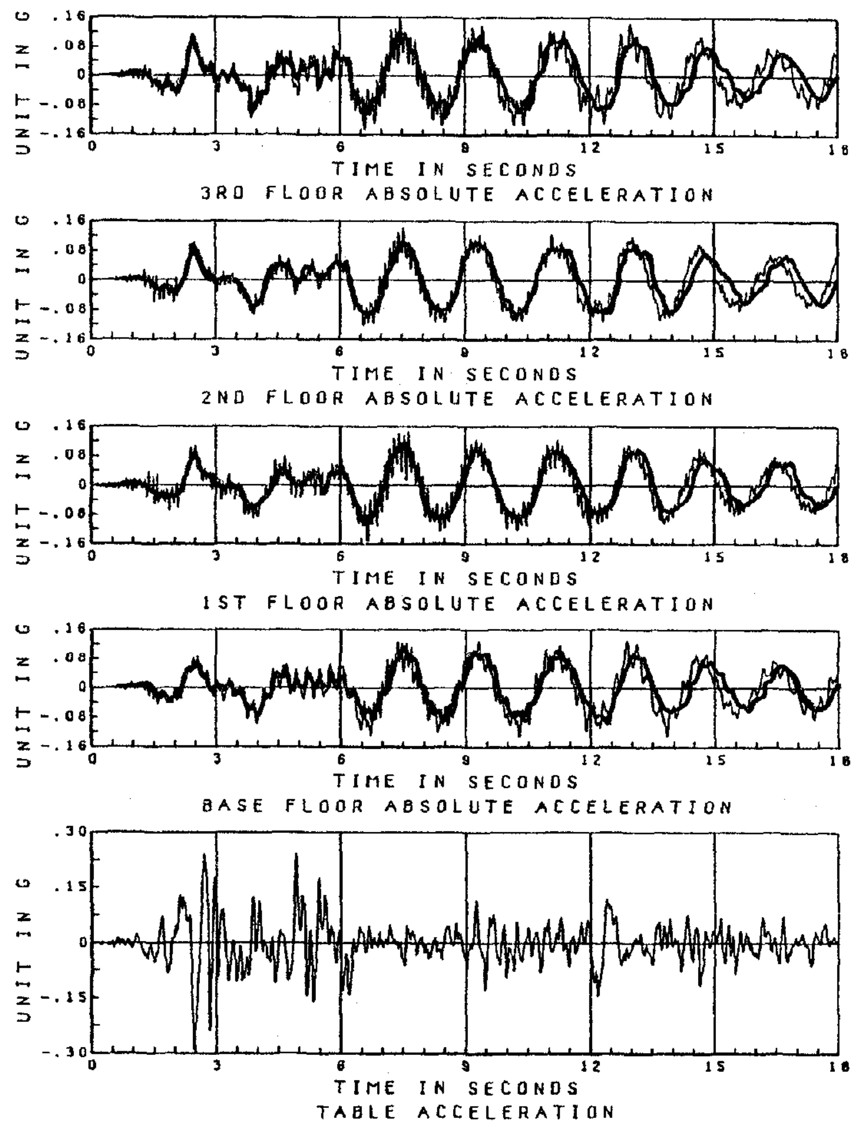


Figure 7.14. RL Base, Accelerations with (——) and without (▬▬)

Vertical Motion, El Centro 400 Horizontal, 350 Vertical

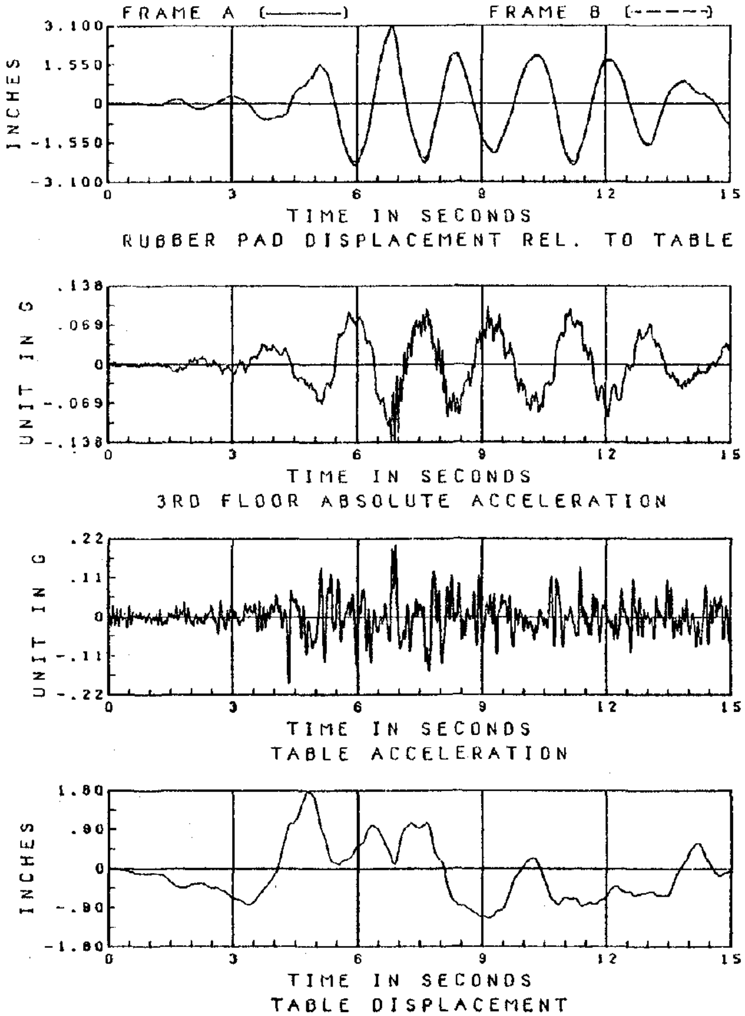


Figure 7.15. RL Base, General Response, Taft 350

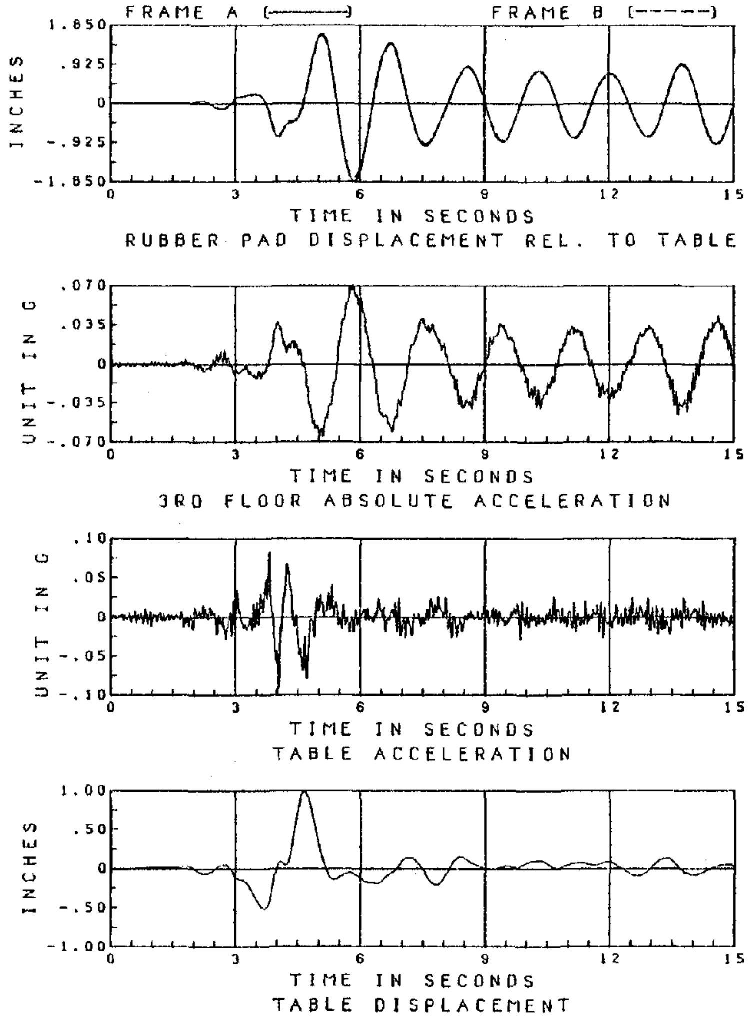


Figure 7.16. RL Base, General Response, Parkfield 200

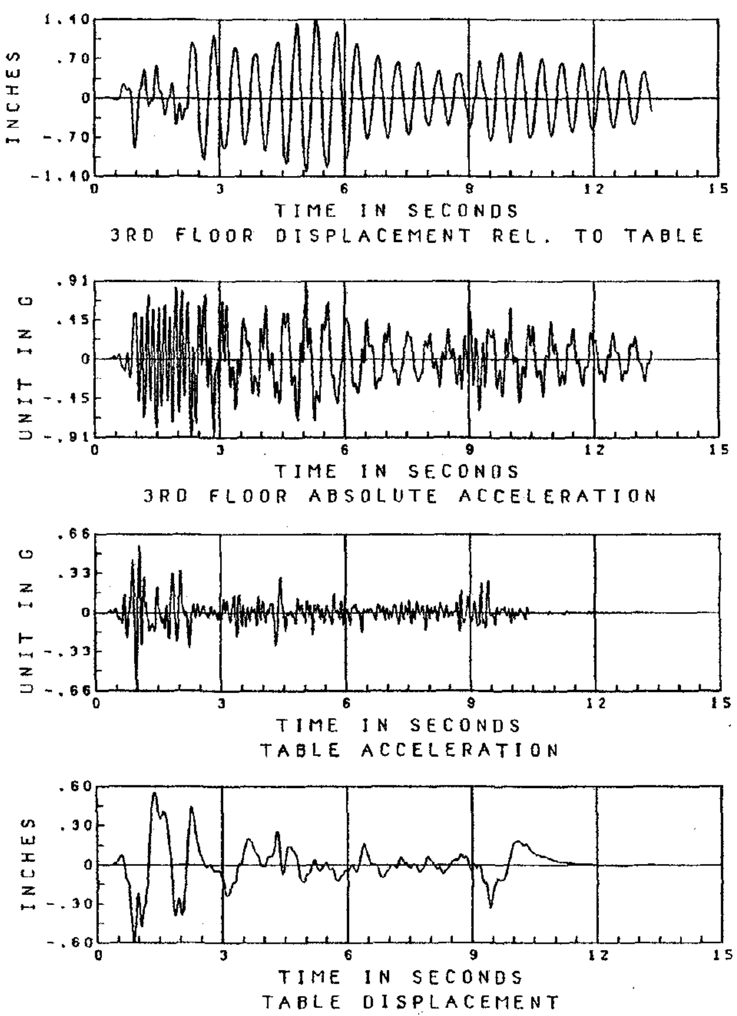


Figure 7.17. Fix Base, General Response, El Centro 120 Time Scaled

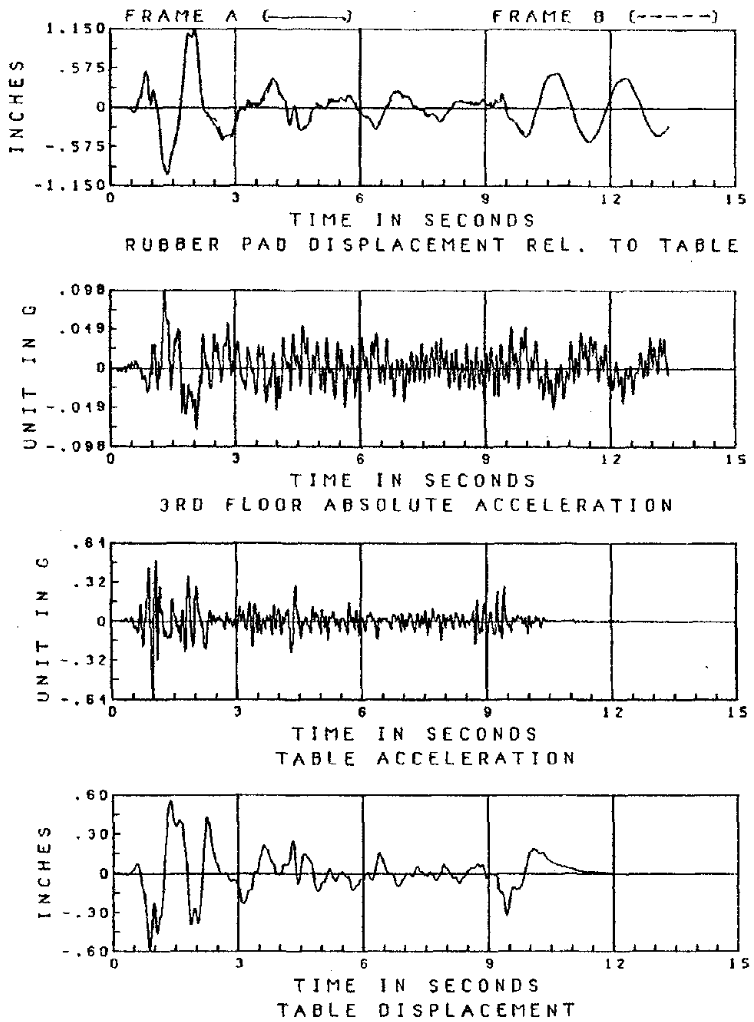


Figure 7.18. RL Base, General Response, El Centro 120 Time Scaled

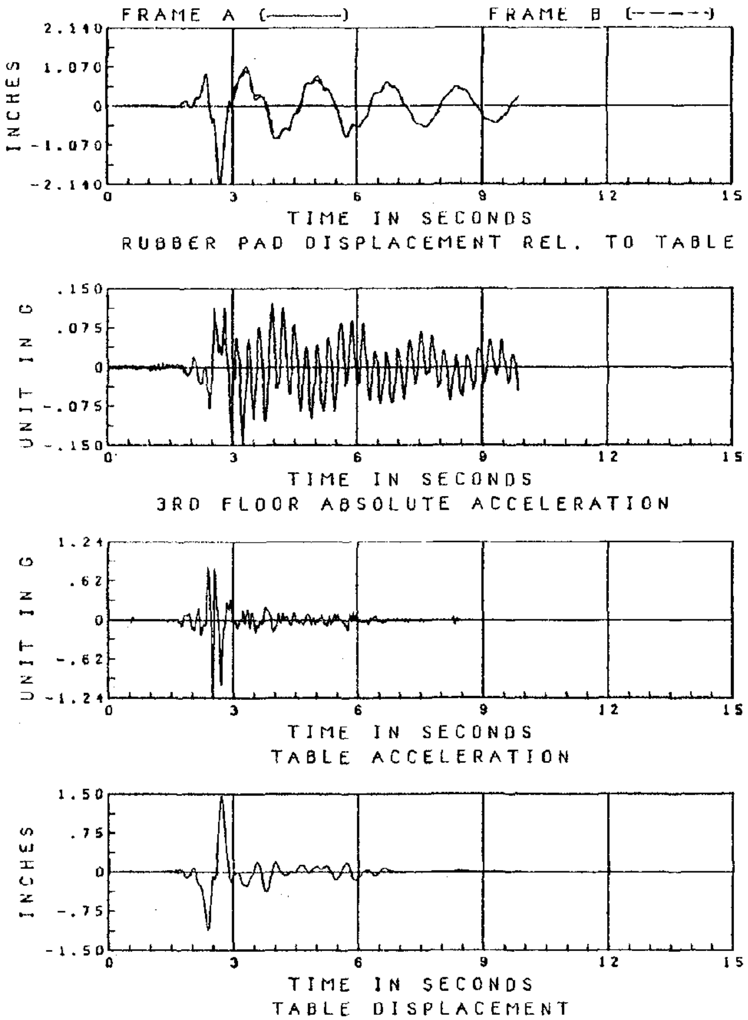


Figure 7.19. RL Base, General Response, Parkfield 280 Time Scaled

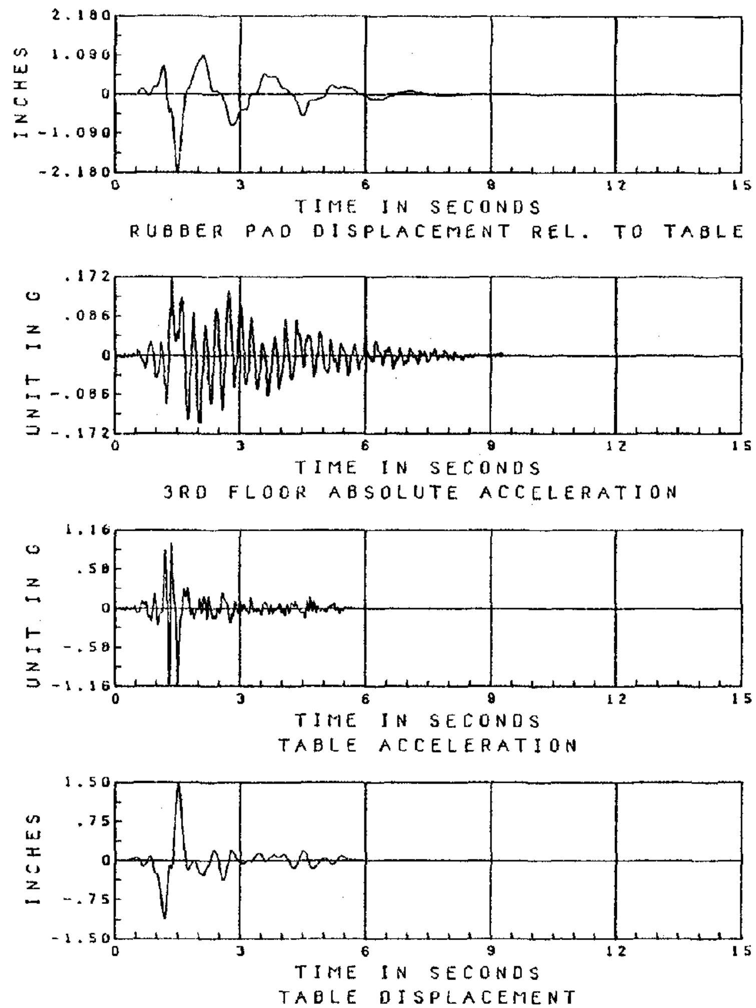


Figure 7.20. R-S Base, General Response, Parkfield 280 Time Scaled

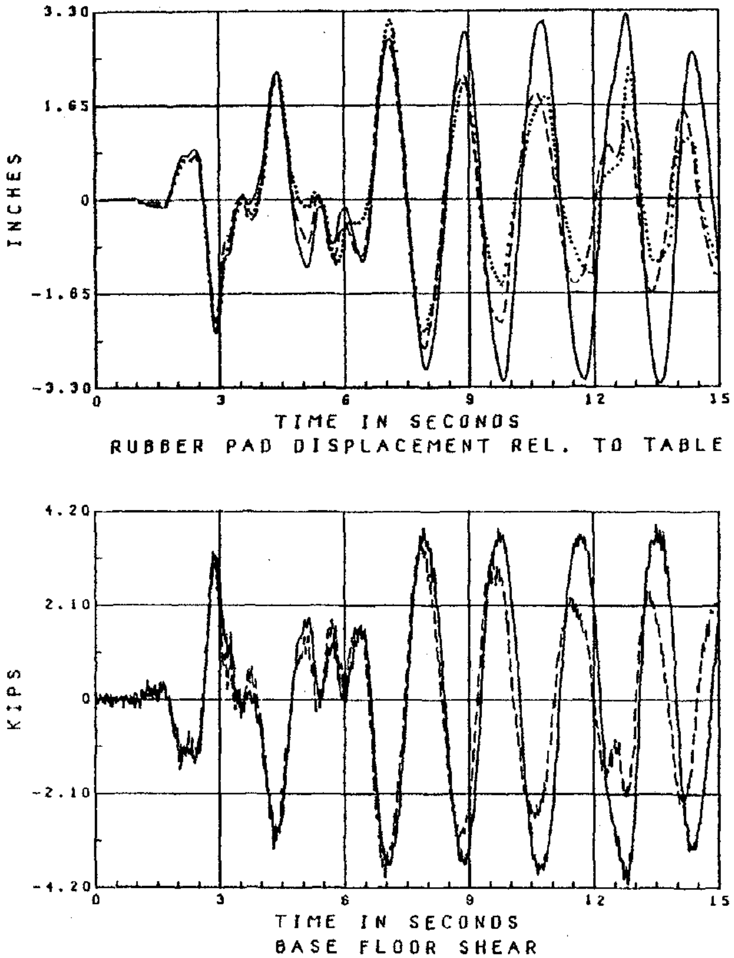
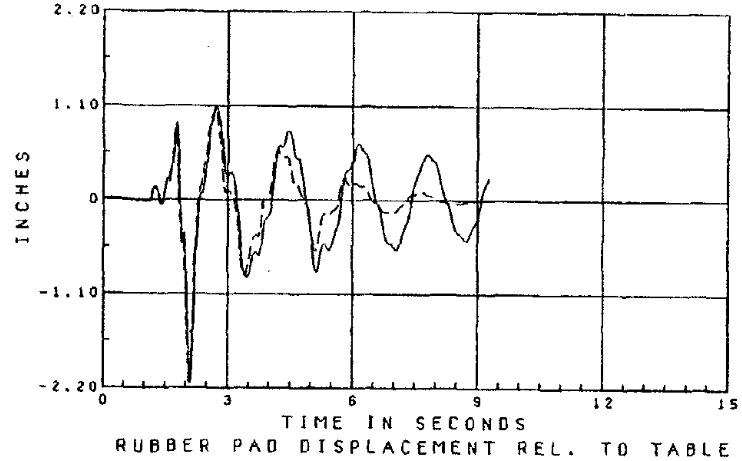


Figure 7.21. El Centro 450, RL (——), RH (····), R-S (---)



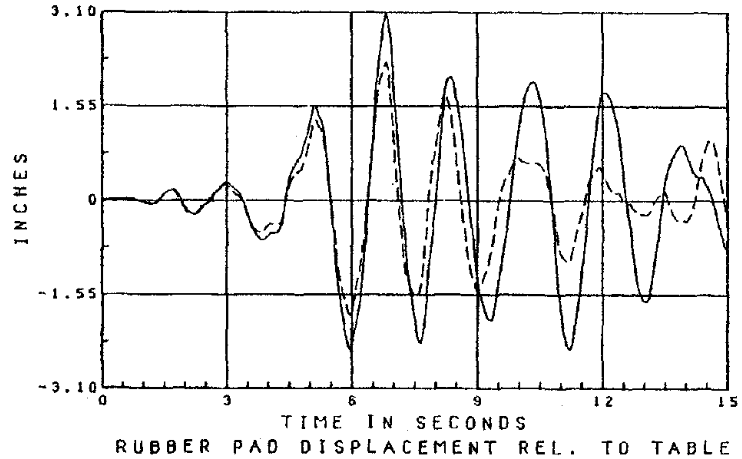


Figure 7.22a. Parkfield 280 Time Scaled, RL (——), R-S (---)

Figure 7.22b. Taft 350, RL (——), R-S (---)

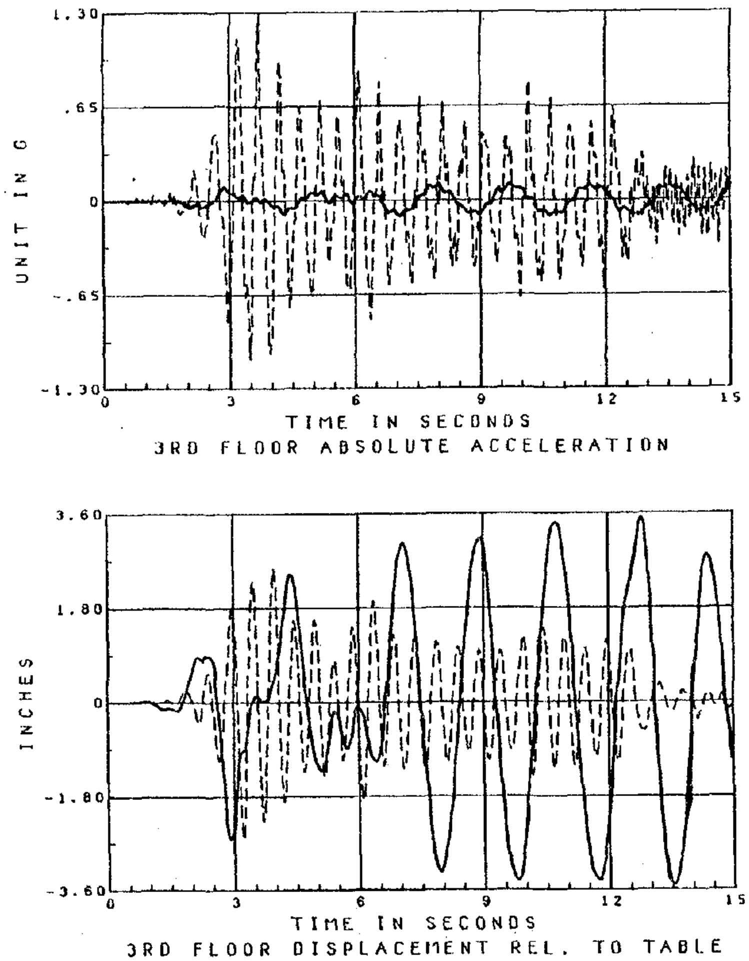


Figure 7.23. El Centro 450, FIX (---), RL (——)

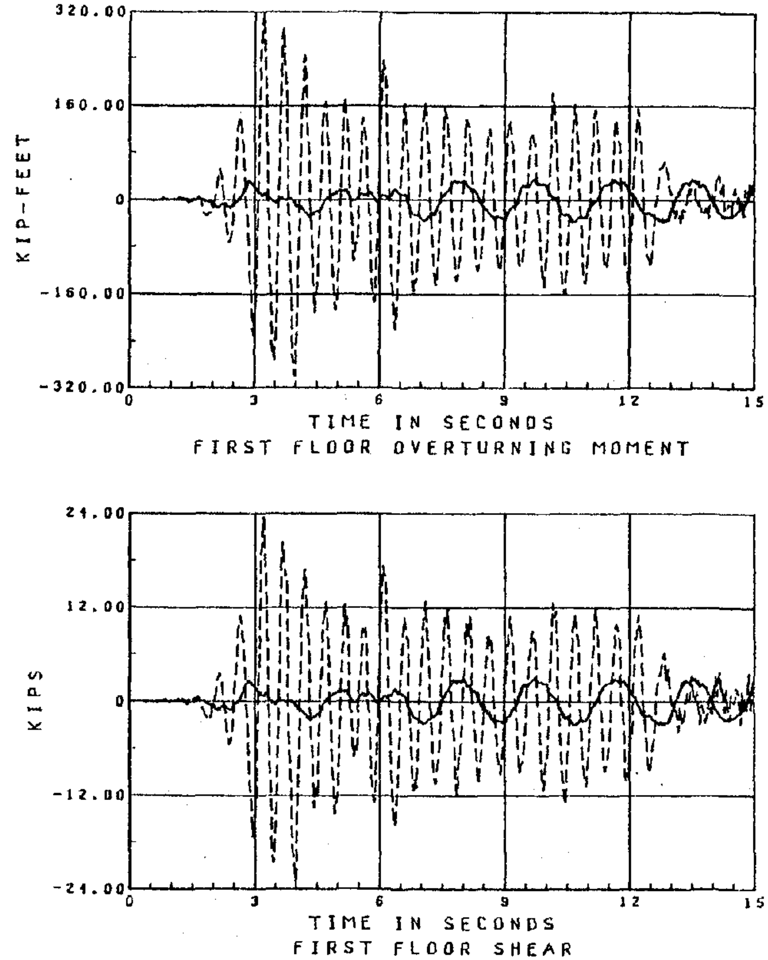


Figure 7.24. El Centro 450, FIX (---), RL (——)

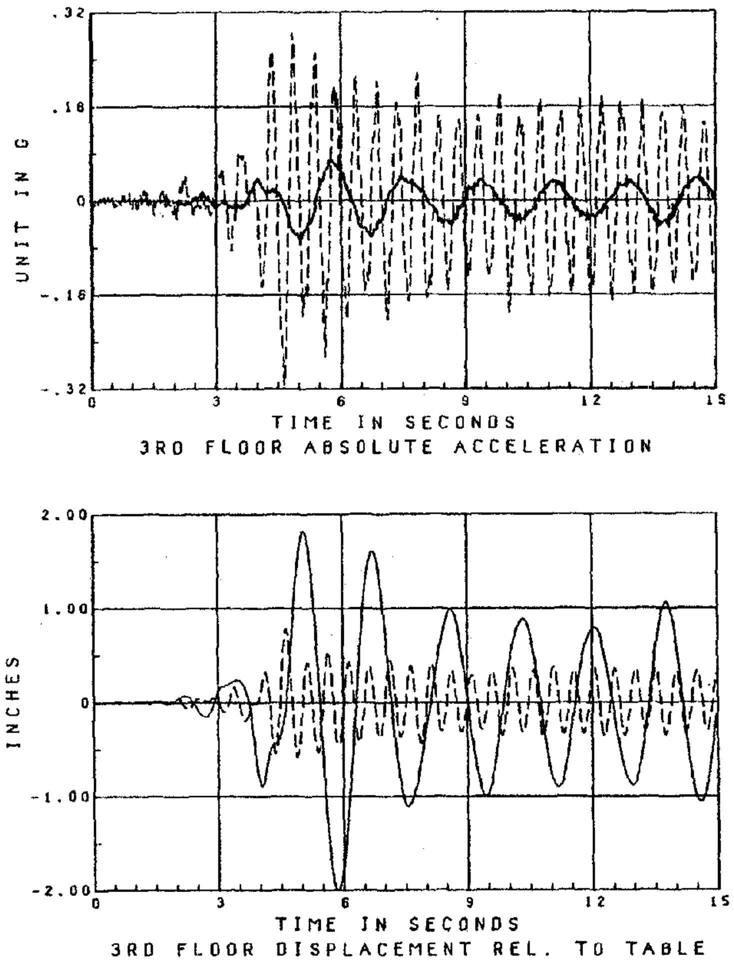


Figure 7.25. Parkfield 200, FIX (---), RL (——)

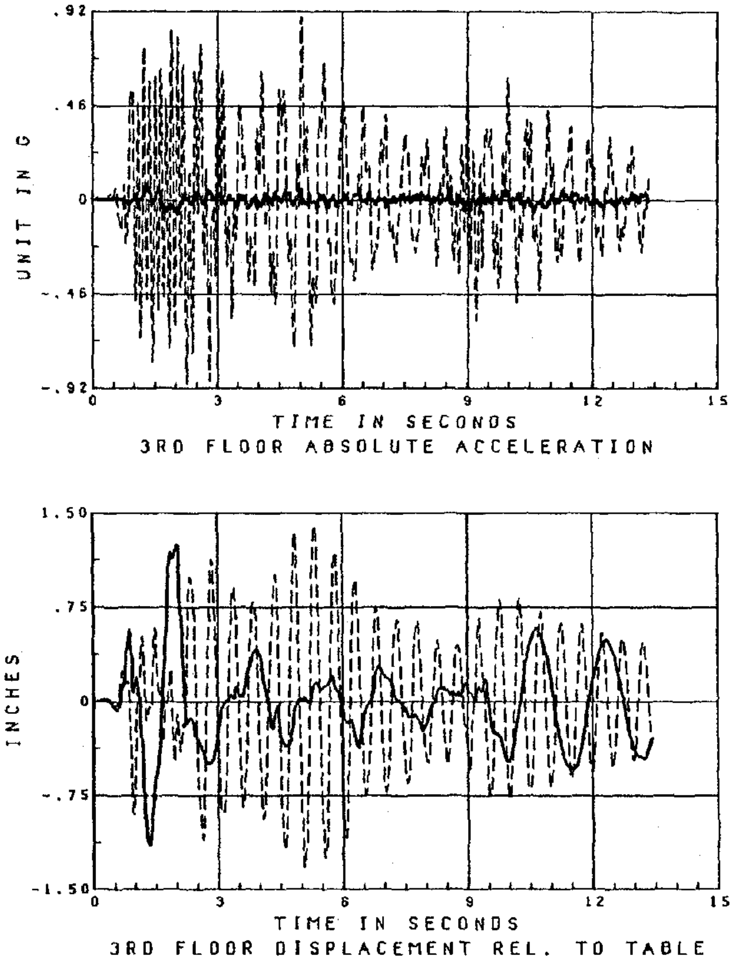


Figure 7.26. El Centro 120 Time Scaled, FIX (---), RL (——)

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