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A DISPLACEMENT CONTROL AND UPLIFT RESTRAINT DEVICE FOR BASE ISOLATED STRUCTURES

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SUMMARY

A displacement control device that can be installed within multilayer elastomeric base isolation bearings is described. The device acts to limit the displacement of the bearings and can also be used to take uplift tension forces if necessary. The device was tested in earthquake simulator tests of a nine-story, 1/4-scale steel frame model, conducted at the Earthquake Simulator Laboratory of the Earthquake Engineering Research Center, University of California, Berkeley. The model was isolated using eight multilayer elastomeric bearings, four of which were located at the corners of the model and contained the displacement control devices. The system was subjected to a large number of simulated earthquakes. In some tests the design acted to control the displacements and in others where uplift forces at the corners were generated the devices simultaneously limited the displacements and carried the uplift forces.

The test results show that the action of the devices is smooth and that there is no sudden jerk when one comes into action. The devices can perform as a fail-safe system for base-isolated buildings and in this role they would be designed to act only when the ground motion is greater than that for which the base isolation system has been designed.

INTRODUCTION

Base isolation is becoming a widely accepted seismic design strategy for low-rise, stiff buildings in seismic regions. However, it has generally been accepted that elastomeric isolators should not be expected to resist tension forces. A medium-rise building, even when isolated, could generate an overturning moment that would cause uplift on some isolators. If a method could be devised to enable the elastomeric isolators to sustain tension then the technique could be extended to a building with a larger number of stories than has so far been contemplated, provided that the superstructure of the building is sufficiently stiff.

Some tension capacity in the isolation bearings would be advantageous for both low-rise and medium-rise buildings for another reason. It would provide a fail-safe system for limiting the maximum displacement of the isolators. This is important since for a fixed-base design, member ductility and design redundancy are counted upon to provide overstrength while isolation systems without fail-safe characteristics appear to have only the one line of defense, namely that of the isolation system.

Fail-safe systems to be used with isolation systems have of course been designed. In some, the building comes against a stop when a certain displacement is exceeded [1]. In others, sliding surfaces come into contact beyond a specified horizontal displacement [2]. In this paper a new fail-safe system will be described and shown that it is effective and practical. The system fits within a standard elastomeric bearing requiring no modification of the foundation or surrounding retaining wall. Its effectiveness has been demonstrated by tests on the earthquake simulator at the Earthquake Engineering Research Center (EERC) of the University of California at Berkeley. It has been used in an isolation system tested under a tall steel frame model which, under moderate earthquake loading, generated uplift forces on the bearings.

PROPERTIES OF THE TEST STRUCTURE

The shaking table experiments were carried out on a nine-story three-bay welded steel frame model (Figure 1) which represents a section in the weak direction of a typical steel frame building at approximately 1/4-scale. The lowest story of the model was 4 feet (1.22 m) high and the others were 3 feet (0.91 m) high. The top of the model was almost 29 feet (8.84 m) above the top of the isolation bearings and the width of the model was 18 feet (5.49 m). The aspect ratio was large enough that the model would experience uplift in the corner columns with moderate accelerations in the structure. The additional mass necessary for similitude requirements was provided by concrete blocks at each floor level. The total weight of the structure and the concrete blocks was 122 kips (543 kN). The two rows of columns were bolted to stiff wide flange sections (W8x31) which ran the length of the base of the model, and with cross beams these represented the base mat of a prototype structure. The base isolators were placed between these W8x31 beams and the shaking table.

The first two natural frequencies of the model structure in the fixed-base condition were 2.8 Hz and 9.0 Hz. These were determined by taking fast Fourier transforms (FFTs) of the ninth floor horizontal acceleration time history when the model was subjected to a free-vibration pull-back test. In a similar fashion the first three natural frequencies of the base-isolated model were found to be 1.11 Hz, 6.09 Hz, and 13 Hz.

ISOLATION SYSTEM

The isolation system consisted of eight natural rubber bearings of multilaminate construction with a bearing located under each column of the steel frame. The natural rubber compound used in these bearings is designated EDS 39 [3] by the Malaysian Rubber Producers Research Association. It is a high strength lightly filled rubber which has a shear modulus of approximately 100 psi (689 kPa) at 50% shear strain. It is relatively low in damping; the equivalent viscous damping ratio at 50% shear strain is in the range of 5% to 7%.

The bearing design is shown in Figure 2. The bearings are designed with four dowel holes in the top and bottom end plates to provide shear connections between the isolation system and the structure. When the uplift restrainers were not in place the dowel holes contained 3/4-inch (19 mm) long tapered pins. In this configuration the frame was free to uplift and no tension was generated in the rubber.

Each bearing provided a stiffness of 1.6 kips/inch (2.8 kN/cm) at 50% shear strain, or 1.125 inches (28.6 mm) displacement, which provided an isolation frequency for the model of 1.01 Hz. This frequency was too low to generate uplift forces at the corner columns for this model since the isolation system did not permit enough transmission of acceleration to the model to generate tension in the corner columns. In order to increase the likelihood of uplift, lead plugs were inserted in the central holes of the four bearings under the center columns. Lead yields at a stress of approximately 1500 ksi (10,000 MPa) which corresponded to 1.8 kips (8.0 kN) shear load in a lead plug, and at 50% shear strain the effective contribution of each lead plug to the stiffness was 1.6 kips/inch (2.8 kN/cm). With the four bearings filled with lead the isolation frequency at 50% shear strain rose to 1.24 Hz. The increased stiffness and the tendency of the lead plugs to generate response in the higher modes made uplift more probable with moderate table inputs.

UPLIFT RESTRAINT AND DISPLACEMENT CONTROL DEVICE

A device that provides uplift restraint and displacement control was inserted in each of the four corner bearings (Figure 3). It consists of two high-strength bolts contained in a cylindrical sleeve that allows a certain amount of free movement of the bolts. The devices have hemispherical ends held in hemispherical recesses which were machined into the 1 inch (25.4 mm) thick top and bottom plates of the bearings. When the bearing is not displaced the bolt heads are together in the center of the sleeve and when the bearing is displaced through a preselected distance the device becomes taut. Since uplift occurs at maximum displacements the device will also resist the uplift forces in addition to acting as a displacement control device. A further modification necessary to enable the bearing to resist uplift is that the four dowel holes in each end plate be threaded and the bearing firmly connected to the foundation and to the superstructure. If displacement control only is needed it is unnecessary to bolt the bearings to the foundation and the superstructure and dowels can be retained to transfer shear loads. It should be noted that the lead plugs in the center four bearings were used in these tests only for the purpose of producing uplift at the corners at moderate levels of earthquake input. They are not an essential component of the isolation system.

As mentioned above, the uplift restraint and displacement control device can move a certain distance within the cylindrical sleeve before going taut. When the bearing has displaced horizontally through this distance the bolt heads are constrained by the ends of the sleeve and at this displacement the horizontal stiffness of the bearing is greatly increased. While this results in a sudden increase in stiffness there is not a sudden stop because, although the restraint device is now inextensible, the bearing can continue to deform horizontally by deforming vertically at the same time. Thus, the horizontal stiffness which is normally low becomes comparable with the much higher vertical stiffness.

Tests were performed on individual bearings in a testing device which applied a constant axial load to the bearings while forcing them through several cycles of constant amplitude sinusoidal displacement. Force versus displacement curves were obtained from these tests at several different displacement amplitudes (Figure 4). Possibly because of friction between the device and the surface of the hole in the bearing, the transition from the stiffness at low shear strain to the combined stiffness of the bearing and the restrainer device at high shear strains was smooth. This smooth transition in stiffness at the initial operating displacement (u_d) of the device had the effect of minimal excitation of higher structural frequencies and led to a far better structural response than might have been expected if the stiffness had been sharply bilinear.

A linear elastic analysis of the response of the bearing with the device was carried out taking into account the vertical and horizontal stiffnesses of the natural rubber bearing, the displaced geometry of the bearing (Figure 5), and assuming small strains in the steel restrainer and a constant axial dead load (W) on the bearing. With these assumptions the following relationship for force versus displacement of the uplift restrainer bearing was obtained. The derivation is given in Reference [4].

$$F_x = k_h u_x \qquad \text{for } u_x \leq u_d$$

and

$$F_x = k_h u_d + \left[k_h + \frac{k_v u_d^2}{h^2 + \frac{k_v}{k_d} L^2} \right] e_x \qquad \text{for } u_x \geq u_d$$

$$\text{with } u_d = \left[L^2 - h^2 \right]^{\frac{1}{2}} \text{ and } u_x = u_d + e_x \, ;$$

where the terms are defined as

P = axial force in the restrainer device;

F_x = shear force applied to the bearing;

W = axial dead load on bearing;

L = length of restrainer device when $P = 0^+$;

k_v = vertical stiffness of bearing;

k_h = horizontal stiffness of bearing;

k_d = axial stiffness of restrainer device;

u_x = horizontal displacement of bearing;

u_d = horizontal displacement of bearing when $P = 0^+$;

δ_y = decrease in height of bearing due to W; and

h = total height of rubber $- \delta_y$.

The curve predicted by these equations is shown in Figure 4.

TEST PROGRAM

In order to study the effectiveness of the uplift restraint device the model was subjected to three different earthquake signals on the shaking table. The earthquake characteristics ranged from predominantly low frequency ground motion (Mexico City and Bucharest) to moderately high frequency ground motion (El Centro). The earthquake test signals used were digitized records based on the earthquake ground motion data recorded at the sites listed below.

(1) Imperial Valley Earthquake (El Centro) of May 18, 1940 — S00E component, peak ground acceleration (PGA) = 0.35g.

(2) Bucharest Earthquake (Building Research Institute) of March 7, 1977 — EW component, PGA = 0.21g.

(3) Mexico City Earthquake (Mexico City Station SCT) of September 19, 1985 — S60E component, PGA = 0.20g.

The records were time-scaled (compressed) by a factor of two to satisfy similitude requirements for the 1/4-scale model.

Table 1 lists the input signals used in the testing program and the maximum model responses to the input signals for the tests on the model in the free-to-uplift condition. Table 2 lists the maximum responses of the model when it was restrained against uplift.

TEST RESULTS

Each earthquake input signal was run at increasing levels of peak table acceleration until the model lifted off the unrestrained corner bearings. Time histories of column vertical displacement (Figure 6) showed that column uplift of 0.75 inch (19 mm) occurred during the El Centro PGA = 0.842g test. This result for the 1/4-scale model implied 3 inches (76 mm) of column uplift of the corner columns in a corresponding full-scale structure. The Mexico City PGA = 0.217g test caused 0.47 inch (12 mm) column uplift and the Bucharest PGA = 0.348g test caused 0.61 inch (16 mm) column uplift. It should be noted that column uplift occurred at the time of peak horizontal displacement. Also associated with column uplift were large vertical accelerations which were generated in the structure when the structure dropped back to its foundation. Vertical accelerations of approximately 1g occurred in the model when the structure was subjected to the El Centro motion which caused 0.75 inch (19 mm) column uplift.

Although the bearings dissipated little energy axially during the uplift motion they did continue to dissipate energy in shear. The column uplift distorted the shapes of both the shear and axial hysteresis loops (Figure 7). The effect of column uplift on the axial hysteresis loop is clear — the vertical displacement of the column base increased from about 0.1 inch to about 0.75 inch (2.5 - 19 mm) without any change in the axial load on the bearing. Column axial load appears to have more of an effect on the shear hysteresis loop when it comes back into contact with the bearing than when it lifts off the bearing. Keeping in mind the fact that positive horizontal displacement corresponds to tensile axial load on the bearing, the shear hysteresis loop appears to become unstable at the time of maximum compressive load (15 kips (67 kN) due to overturning plus the bearing dead load of 8 kips (36 kN)). This was probably due to the combination of a decrease in the thickness of the rubber layers and a sudden drop in shear stiffness because of the sudden increase in axial load on the bearing. This phenomenon would probably only be observed in cases where the axial loads approach the buckling load. Nevertheless, this behavior is clearly undesirable since any sudden drop in the stiffness of the isolation system could result in significantly larger bearing displacements.

Although significant column uplift occurred during the largest magnitude tests using the three test signals the bearing shear connection did not uncouple as had happened during previous tests performed on a base-isolated reinforced concrete structure [5]. Recognizing the importance of preventing uncoupling of the bearings during extreme uplift events, longer dowels were designed for this test series to overcome the problem. A dowel length of 0.75 inch (19 mm) was used, and this proved to be sufficient to prevent uncoupling.

After the tests on the free-to-uplift structure were completed the unrestrained corner bearings were replaced by bearings containing the uplift restrainer device. The model was then subjected to the same set of earthquake ground motions. The records of corner column vertical displacement (Figure 6) and horizontal bearing displacement confirm that the restrainer device not only prevented the uplift seen previously but also essentially limited the relative horizontal displacement of the structure to the free displacement of the restrainer device.

The peak story acceleration profiles are plotted for the El Centro tests on the isolated structure with and without the displacement control device (Figure 8). For the shaking table inputs which did not cause the restrainer device to go into tension the profiles are similar in shape to the free-to-uplift profiles. The acceleration profiles for the tests which had peak table accelerations similar to those in the tests on the free-to-uplift model where uplift occurred are different. The magnitude of the peak roof acceleration when the displacement control device was activated was almost double for the El Centro test signal.

The restrainers also reduced the magnitude of the vertical acceleration response from approximately 1g in the free-to-uplift test to approximately 0.3g. The effect of the restrainer on the shape of the axial and shear force hysteresis loops for a restrained bearing is seen in Figure 9. Both hysteresis loops are now stable and the shear loop reflects the bilinear stiffness properties characteristic of the displacement control device.

CONCLUSIONS

Although earthquake simulator tests have been performed previously to evaluate base isolation systems, these studies were all performed on short stiff structures. Base isolation has not been proposed for taller buildings because of the obvious problems of column uplift and longer structure period.

The displacement control device described herein successfully restrains columns from uplift during earthquake motions having magnitudes which previously caused column uplift in the unrestrained nine-story steel frame model. The device was installed within the hollow core of a multilayer elastomeric bearing and was placed under each corner column of the base-isolated structure. The interior columns were supported by the similar bearings but without the displacement control device. The devices were set to allow only 2.25 inches (57.2 mm) of free horizontal displacement before they were fully extended, thereby limiting further horizontal displacement because of the increased horizontal stiffness of the isolation system. The vertical component of force in the device served to restrain the column against uplift.

For earthquake tests during which the device extended fully, the maximum story accelerations were about double those for similar input signal magnitudes where the device had not been installed. The higher frequency responses of the structure were not increased at the times when the device was fully extended because of the smooth transition in the horizontal bearing stiffness.

While column uplift was the primary concern in the isolation tests on the nine-story steel frame, the uplift restrainer devices could clearly also be used for horizontal displacement control. The devices would act in this capacity as a fail-safe mechanism, and would be designed to come into effect only when the bearing displacement exceeded the maximum allowable displacement or the design displacement of the isolation system.

ACKNOWLEDGEMENTS

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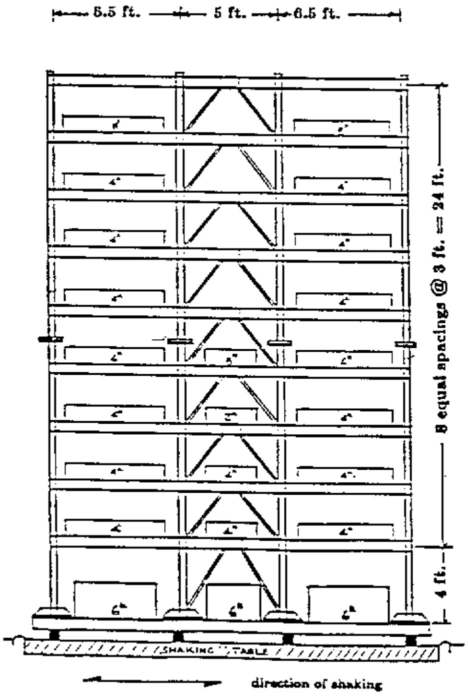
FILE NO.	RUN	SPAN	PK. TABLE ACCEL. (g)	PK. MODEL ACCEL. (g)	REL. BEARING DISPL. (in.)	UPLIFT (Y/N)
860708.03	$\sqrt{4}$ ec	150	.313	.244	.904	N
860708.04	$\sqrt{4}$ ec	225	.460	.288	1.712	N
860708.05	$\sqrt{4}$ ec	300	.604	.453	2.648	Y
860708.06	$\sqrt{4}$ ec	400	.842	.607	3.784	Y
860709.01	$\sqrt{4}$ buc	275	.241	.293	1.825	N
860709.02	$\sqrt{4}$ buc	350	.296	.444	2.729	Y
860709.03	$\sqrt{4}$ buc	400	.343	.537	3.259	Y
860709.04	$\sqrt{4}$ mex	175	.146	.254	1.898	N
860709.05	$\sqrt{4}$ mex	250	.194	.425	3.063	N
860709.06	$\sqrt{4}$ mex	275	.219	.586	3.372	Y
860709.07	$\sqrt{4}$ mex	275	.217	.520	3.416	Y

buc = Bucharest signal; ec = El Centro signal; mex = Mexico City signal.

Table 1 Maximum Model Responses on Bearings without Displacement Control Device

FILE NO.	RUN	SPAN	PK. TABLE ACCEL. (g)	PK. MODEL ACCEL. (g)	REL. BEARING DISPL. (in.)	UPLIFT (Y/N)
860711.03	$\sqrt{4}$ ec	150	.336	.279	.637	N
860711.04	$\sqrt{4}$ ec	225	.487	.341	1.150	N
860711.05	$\sqrt{4}$ ec	225	.420	.372	1.313	N
860711.06	$\sqrt{4}$ ec	300	.627	.503	1.930	N
860711.07	$\sqrt{4}$ ec	350	.726	.727	2.451	N
860711.08	$\sqrt{4}$ ec	400	.832	.851	2.958	N
860711.09	$\sqrt{4}$ buc	400	.351	.620	2.854	N
860711.10	$\sqrt{4}$ mex	275	.168	1.524	3.635	N

Table 2 Maximum Model Responses on Bearings with Displacement Control Device



1 foot = 0.305 m

FIGURE 1 NINE STORY STEEL TEST FRAME

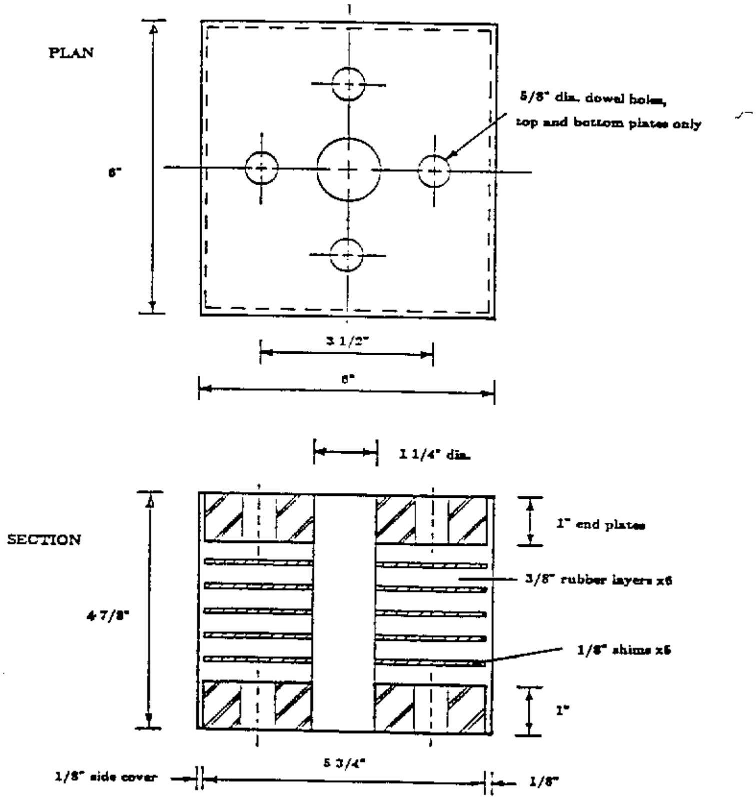


FIGURE 2 LEAD PLUG BEARING DETAILS

1 inch = 25.4 mm

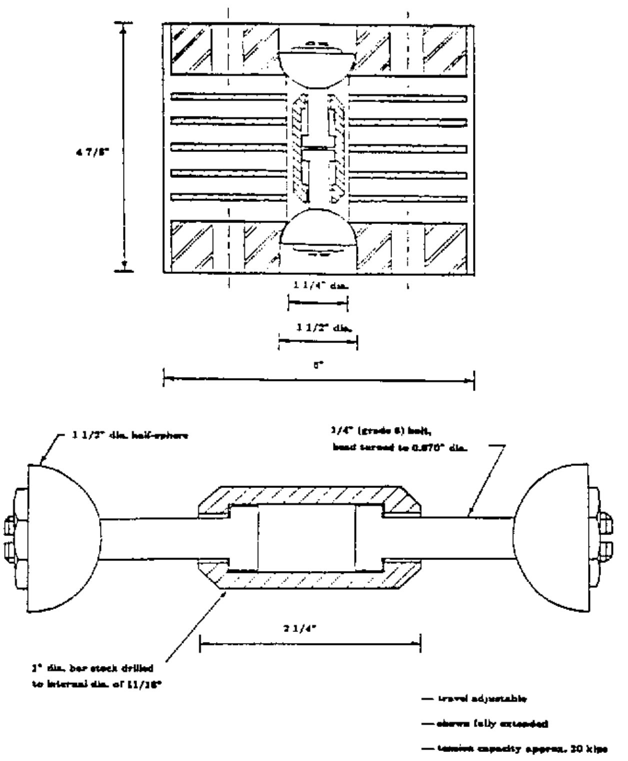


FIGURE 3 BEARING MODIFIED TO ACCEPT DISPLACEMENT CONTROL DEVICE

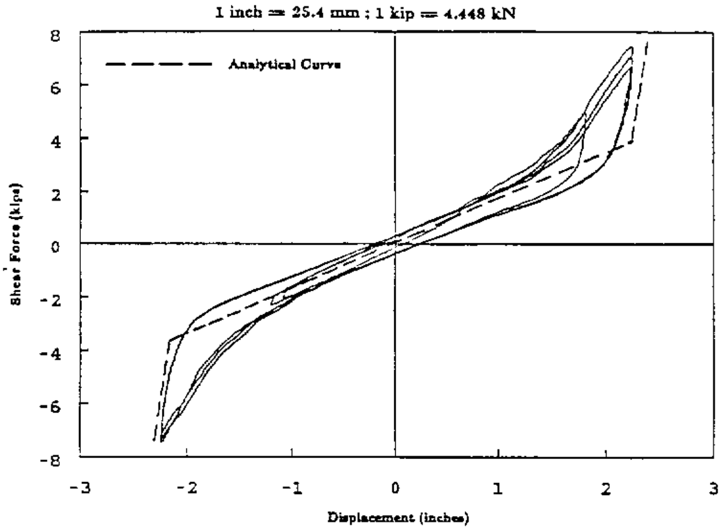


FIGURE 4 EXPERIMENTAL AND PREDICTED FORCE-DISPLACEMENT CURVES FOR RESTRAINED BEARING

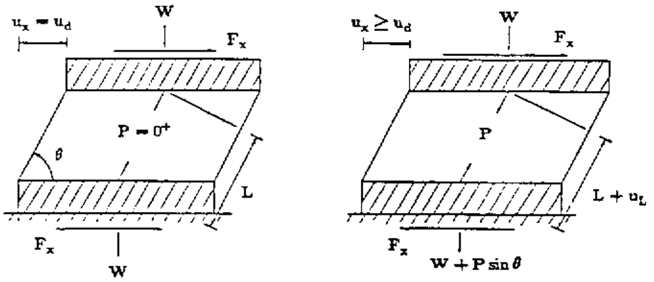


FIGURE 5 RESTRAINER BEARING FORCE DIAGRAM

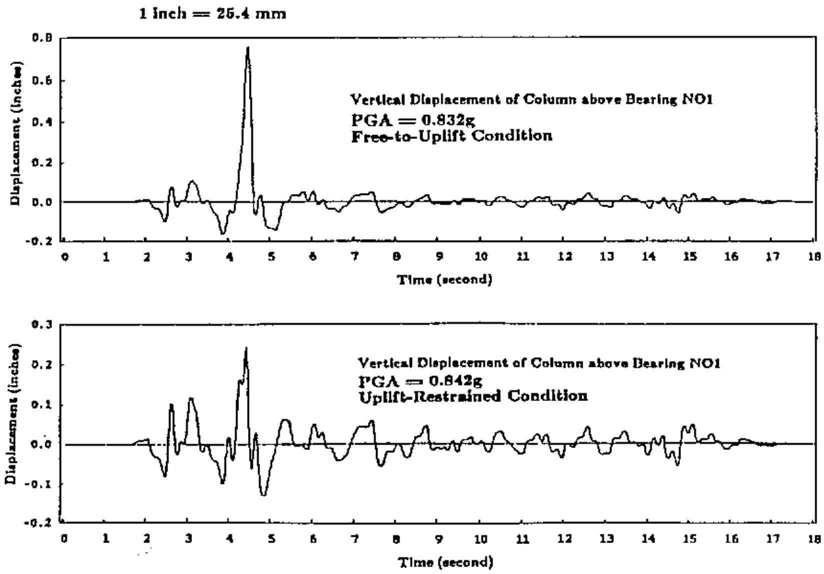
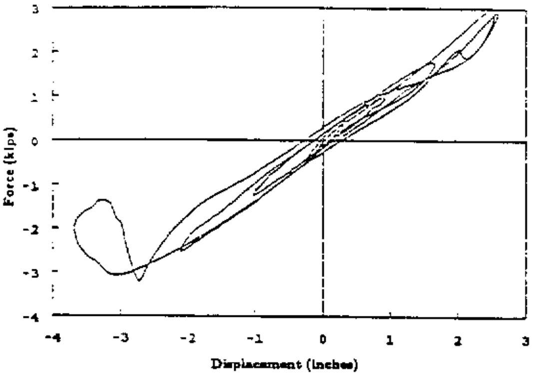
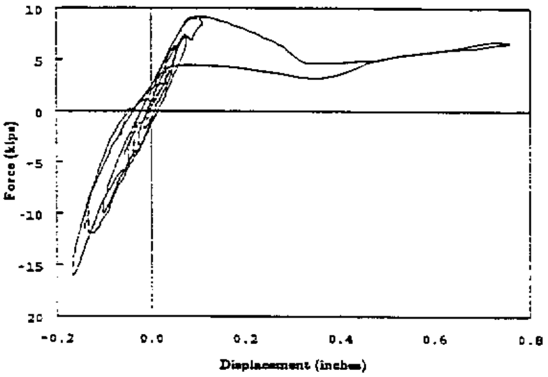


FIGURE 6 COLUMN VERTICAL DISPLACEMENT DURING EL CENTRO TESTS



(a) Shear Force vs. Horizontal Displacement

1 inch = 25.4 mm ; 1 kip = 4.448 kN



(b) Axial Force vs. Vertical Displacement

FIGURE 7 SHEAR AND AXIAL FORCE BEHAVIOR OF BEARINGS IN FREE-TO-UPLIFT CONDITION DURING EL CENTRO, PGA = 0.842g

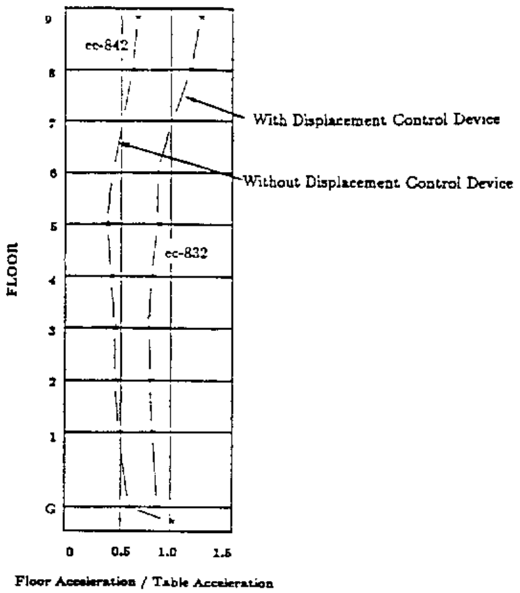
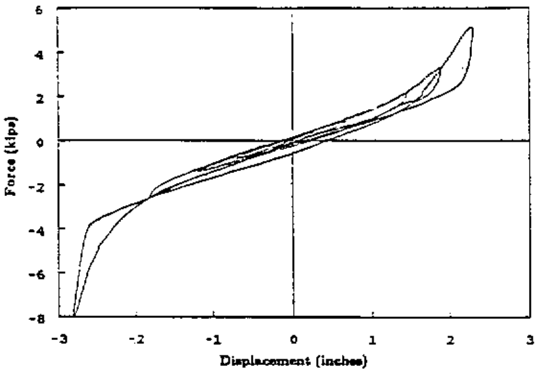
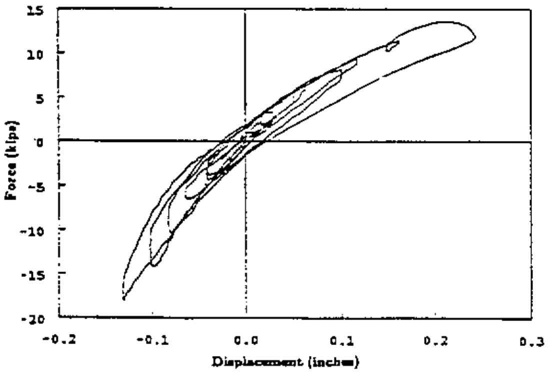


FIGURE 8 PROFILES OF PEAK STORY ACCELERATIONS FOR THE FREE-TO-UPLIFT AND UPLIFT-RESTRAINED ISOLATION CONDITIONS



(a) Shear Force vs. Horizontal Displacement

1 inch = 25.4 mm ; 1 kip = 4.448 kN



(b) Axial Force vs. Vertical Displacement

FIGURE 9 SHEAR AND AXIAL FORCE BEHAVIOR OF BEARINGS IN UPLIFT-RESTRAINED CONDITION DURING EL CENTRO, PGA = 0.832g