EXPERIMENTAL STUDIES OF THE SEISMIC RESPONSE OF STRUCTURES INCORPORATING BASE ISOLATION SYSTEMS

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Whereas the concept of base isolating structures from the damaging effects of earthquake motions is not new, implementation of the technique is a relatively new occurrence. This has mainly been due to the need for several important developments in materials science and experimental and analytical modeling before base isolation could evolve into a practical approach for seismic design.

One of these developments has been the ability to test large-scale isolation systems using simulated seismic loads. These tests have not only proven the performance and reliability of the isolation systems and hardware, but have enabled correlation studies to be undertaken which have confirmed the accuracy of analytical methods and the acceptability of current design procedures. The Earthquake Engineering Research Center (EERC) at the University of California at Berkeley has been an active participant in this work, and this paper reviews some of the achievements of the Center in the last few years.

Component tests on single isolators are described. Tests on plain and high damping natural rubber bearings, lead-rubber bearings, sliding bearings, and bearings incorporating uplift resistance mechanisms have been performed. High-shear strain tests on large (up to full scale) elastomeric bearings have been conducted to determine the stability characteristics and limit states of the isolators.

Performance evaluation studies using the earthquake simulator to test large-scale model isolated structures have been carried out for a variety of isolation systems and structures. Uplift studies of slender base-isolated buildings and investigation of the behavior of base-isolated skew bridge decks have been studied. This paper aims to highlight those areas where progress has been made.

Introduction

Base isolation is a seismic design strategy for reducing the effects of earthquake ground motions on structures by uncoupling the structure from the horizontal components of the earthquake motion while at the same time supporting the gravity weight of the structure. In recent years much effort has been devoted to base-isolation research[1] and there has been a growing acceptance of the approach. It is being incorporated in an increasing number of projects worldwide.[2]

Essential requirements of any base-isolation system include fixity against wind loadings and low-level shaking, stability for all possible loadings, and a fail-safe capability in its ultimate limit state. To be feasible any system must be shown to incorporate these features.

The objective of experimental research in base isolation at EERC in recent years has been to verify the performance, reliability, and repeatability of behavior of components for isolation systems; to develop methods for modeling system behavior for design purposes; to investigate unusual aspects of behavior of various systems (especially during extreme conditions of loading); and from the wealth of data available to examine the suitability of proposed code provisions to accurately predict behavior for design.

Component Tests of Isolators

Two test rigs have been designed to subject elastomeric bearings to combined static vertical and cyclic lateral loads. The first rig (Fig. 1) is capable of testing small single bearings and has been used extensively in conjunction with earthquake simulator studies of isolation systems to provide information on bearing stiffness and damping properties and the variation of these properties with frequency and shear strain. The test bearing is simultaneously subjected to a constant (but variable from test to test) vertical load and a cyclic shear load of variable amplitude and frequency. The forces to which the bearing is subjected are recorded by a three-way force transducer located under the bearing and shear (horizontal) and vertical displacements are also measured. Shear and axial hysteresis loops and force and displacement time histories can be plotted from the recorded data.

More recently, a much larger bearing test rig (Fig. 2) has been designed to test large- to full-scale bearings. This rig tests four bearings at one time, a configuration that minimizes the need to resist large external reaction forces by loading one pair of bearings against the other. The rig is capable of applying up to 1500 kips vertical load and, depending on configuration, can load bearings laterally up to 18 in. These limits make it possible to test bearings up to about 30-in. diam and about 15 in. high, which are typical sizes for full-size bearings. Recent tests of a set of 26-in.-diam bearings showed stable behavior under combined vertical and lateral loads to shear strains of 200% (Fig. 3).

Earthquake Simulator Studies

1. Uplift of Medium-Rise Structures

To date, applications of base isolation as a seismic design strategy for buildings have been restricted to low aspect-ratio structures for which there is no chance of overturning occurring during extreme ground shaking. In most instances this limitation does not affect designers as, in general, the taller the structure, the less practical it is to use base isolation. Building slenderness has some relation to period but, more important, it plays a large part in determining whether a building will uplift off its base during extreme lateral loadings and this is not something that is accommodated by usual base-isolation devices.

An extensive research program was undertaken to address the question of uplift of base-isolated medium-rise structures. The work was conducted in two phases: the first involved shaking table studies of a medium-rise structure with a base-isolation system allowing free uplift and a detailed evaluation of the behavior of the structure during uplift and the second phase of the program was to consider approaches to avoiding the occurrence of uplift of the superstructure from the isolation system.

1.1. Phase I

Phase I of the uplift investigation program involved the earthquake simulator testing of a 1/5-scale 7-story reinforced-concrete structure[3] (Fig. 4). The model was tested with three different types of high damping natural-rubber-bearing isolation systems and, throughout testing, model was permitted to uplift freely from the bearings. An extensive testing program was performed. Initially, static rig tests of the isolation bearings were carried out to assess the performance characteristics of each type of bearing. The dynamic testing of the model consisted of free vibration tests, harmonic excitation tests, white-noise tests, and earthquake simulation tests using eight different earthquake motions representing a wide variety of ground motions. The input motions ranged from the predominantly high-frequency San Francisco Earthquake of 1957 to the long-period shaking of the 1985 Mexico City and 1977 Romanian Earthquakes. To satisfy model similitude requirements the records were time-scaled by a factor of $\sqrt{5}$. The model was subjected to the time-scaled signals at three levels of peak table acceleration (typically

0.2, 0.5, and 0.8 g) allowing the effect of increasing shear strain in the rubber and the consequent change in structural response of the system to be studied. The effectiveness of the isolation systems was studied as a function of the magnitude of the input motion.

For all inpu motions (and levels of input) the response was observed to be essentially rigid-body translation, an aspect that is important for the basis of simplified code design procedures. Previous tests of the model in a fixed base configuration allowed some comparisons of response to be made and it was seen that the accelerations, interstory displacements and story shears were considerably reduced over those for a fixed base structure.

A comparison of the SEAONC "Tentative Seismic Isolation Design Requirements"[4] with the observed responses of the structure was undertaken to evaluate the suitability of the design formulae for this particular structural system. In particular, consideration was given to the suitability of the SEAONC formula for bearing displacement (D):

$$D = \frac{10ZNST}{B}, \tag{1}$$

where the terms Z, N, S, T, and B are defined as follows:

D = minimum displacement for which the isolation system must be designed;

Z = coefficient related to the seismicity of a region, either 0.3 or 0.4 for California;

N = coefficient related to the proximity of the building or structure to active faults,

S = coefficient related to site-soil profile, ranging between 1.0 and 2.7;

T = period of the isolated structure; and

B = coefficient related to isolation system damping, ranging between 0.8 and 2.0.

In evaluating the proposed code formula one of the objectives was to determine the best coefficient for "ZN" in the design equation, with consideration given to the peak table acceleration (PGA), and the coefficients A_a and A_v as defined by ATC 3-06 (Ref. 5) derived for each of the time-scaled earthquake signals.

It was found that:

1. The velocity-based coefficient A_v was the best measure of the earthquake motion for use in the formula.
2. As is acknowledged, the results showed that the design procedures are not applicable to low-frequency motions.

1.2. Phase II

The concrete model used in phase I of the uplift study had suffered substantial damage when previously tested as a fixed-base structure. The model had been repaired at its base at the time of adding the isolation system and all large cracks in the beam-column joints and the shear wall were injection grouted. The favorable test results from phase I indicated that the rehabilitation work has been successful, but for the more severe testing planned it was decided to use another model structure for phase II (Ref. 6). This structure was a 1/4-scale 9-story braced steel frame (Fig. 5) which, with a height-to-width ratio of 1.59, was more suited to developing high overturning forces during severe shaking.

The model was tested using a number of isolation systems (described in subsequent sections). The isolation system for the uplift study consisted of four lead-rubber bearings under the internal columns and four natural rubber bearings under the corner columns of the model. With this combination of bearings column uplift was achieved at moderate levels of shaking.

For a series of tests maximum model acceleration was plotted against maximum table acceleration and it was found that the structure acceleration to cause corner column uplift was about 0.44 g. Bearing-column separation displacements up to 0.75 in. were observed. The hysteresis loops for the bearings that experienced column uplift exhibited unstable behavior. The shear force hysteresis loops showed dramatic changes in slope and flattening at the extreme displacements while the axial force hysteresis loops had a large increase in displacement (corresponding to times of column uplift) with no change in axial load (Fig. 6). This behavior was felt to be undesirable, especially since the possibility of complete disengagement of the building from the bearing could cause major damage to the structure in that region.

1.3. Uplift Restraint Device

After the series of free-to-uplift tests, bearings containing a device capable of resisting uplift forces[7] were placed under the corner columns of the model and the test program was repeated. The system performed well for all earthquake inputs, and the restrainer device prevented any occurrence of column uplift during severe motions. The nature of the restrainer device was such that it also served to limit horizontal d splacements, and as such the responses of the structure were somewhat higher than for the free-to-uplift condition but the behavior was still very favorable. The hysteresis loops for a bearing containing the restrainer device (Fig. 7) showed stable behavior. The increase in the higher mode contributions to the overall response of the structure (due to the action of the devices) was slight.

2. Performance Evaluation of Isolation Systems

Concurrent with the uplift investigation program, an extensive series of shaking table tests was conducted to evaluate the performance of a number of different base-isolation systems. These systems and some of the notable aspects of the tests are described in the following sections.

2.1. High Damping Natural Rubber Bearings

In conjunction with phase I of the uplift study a series of tests on three types of high damping natural rubber bearing was performed.[3] Each of the bearing types was 6x6 in. in plan but with varying internal configurations. The type-1 bearings had 16 layers of 0.213-in.-thick rubber and a shear stiffness giving the 1/5-scale reinforced-concrete model an isolated frequency (at about 50% shear strain) of 1.1 Hz. The type-2 bearings had 18 layers of 0.198-in.-thick rubber and a shear stiffness providing an isolated frequency of 0.72 Hz at 50% shear strain. The type-3 bearings were of a special light-weight design that was the same in all respects as the type-2 bearings except that the internal shims were only 0.012 in. thick compared with 0.037 in. for the type-2 bearings. High damping natural rubber bearings possess a significantly nonlinear effective stiffness versus shear strain relationship and this provides the isolation system with the required high stiffness at small amplitudes of motion to resist wind loads and low-level shaking while still allowing optimum isolation performance for severe earthquake shaking.

The type-2 bearings were designed to investigate the feasibility of using base isolation in situations of low-frequency ground motion and also the feasibility of using isolation for small buildings (≈50-200 tons). The objective of the type-3 bearing tests was to evaluate the performance of less-expensive lightweight bearings that might be suitable for application to low-cost housing in developing countries.

As an example of the test results for the type-3 high damping bearings, the profile of peak story accelerations for the El Centro signal as input (PGA = 0.405 g) is shown in Fig. 8. The corresponding profile for the fixed-base model subjected to the same input is also shown in the figure. The shear force-displacement relationship for the entire isolation system (8 bearings) during the test is shown in Fig. 9. Results for the complete test program are presented in Table I. It is worth noting that the high damping in the rubber compound is achieved at a relatively low shear modulus, being approximately 63 psi at around 50% shear strain.

All three bearing designs performed well for a large range of earthquake motions and magnitudes of input. In all cases except the predominantly long-period Mexico City signal the isolation systems offered significant reductions in structure acceleration over the peak input acceleration, and interstory displacements (and, hence, story shears) were reduced considerably from those for a fixed-base structure. Small amplifications of acceleration response were observed for the Mexico City tests. It was concluded that the bearings performed extremely well and further analytical and experimental investigation in the area of lightweight bearings is warranted.

2.2. Neoprene Bearings

A neoprene-bearing isolation system has been studied using the 9-story steel test structure as used in phase II of the uplift program.[8] The bearings were 6x6 in. in plan and consisted of six layers of 3/8-in. neoprene separated by five 1/8-in. steel reinforcing shims. The neoprene bearings possessed a significant nonlinearity of shear stiffness with shear strain. At 50% shear strain the bearing shear stiffness was about 2.1 kip/in. and at 2% shear strain the shear stiffness was about two times this value. This nonlinearity made direct comparisons of results from different tests difficult, but assuming a simple proportionality relationship led to the approximate damping value of $\xi = 10\%$ at a frequency of 1.5 Hz and 10% shear strain (or $f = 1.1$ Hz at 100% shear strain).

The performance of the neoprene bearing system was studied for the eight earthquakes as used in previous test programs up to shear strains of 114% and was felt to be excellent. The bearings showed no instability tendencies and the shear force hysteresis loops exhibited stable behavior and no change in stiffness properties even for a large number of displacement cycles exceeding 50% shear strain. The suitability of the SEAONC design formulae for this isolation system was assessed[9] and found to give good conservative results using the A_v coefficient.

2.3. Lead-Rubber Bearings

Following the neoprene-bearing tests, the 9-story structure was base isolated with a system of lead-rubber bearings and subjected to another series of simulated earthquakes. The lead-rubber bearings were geometrically similar to the neoprene bearings, but with the addition of 1.25-in.-diam lead plug inserts. The inherent damping of the natural rubber of these bearings was only about 5-7%, but with the lead plug added, the equivalent viscous damping ratio for a bearing at 50% shear strain was in the range of 20-25%. Each lead-rubber bearing had a shear stiffness of about 3.2 kip/in. (the stiffness of the bearing without the lead plug was 1.6 kip/in.). To achieve a reasonable overall system stiffness only four of the eight bearings of the isolation system were provided with lead plugs.

Because of the inherently higher shear stiffness of the lead-rubber bearings the degree to which the isolated building responded in its first mode was of particular interest. Test results showed that the first mode response did indeed dominate, thus confirming that the simplified code design approach is applicable to this type of structure and isolation system.

2.4. Combination Slider-Elastomeric Bearing System

This isolation system was tested using the 9-story steel structure and consisted of uplift-restrainer bearings under the four corner columns and Teflon stainless-steel slider bearings situated under the interior columns of the model.[10] The system provided significant reductions in story acceleration and base shear from the levels expected in a similar structure with a fixed base support. The uplift restrainer bearings allowed no column uplift during the tests and the slider bearings reduced displacements from those seen for other isolation systems. The behavior contrasted that of a purely sliding system in that the elastomeric bearings ensured that the isolation system as a whole did not suffer any significant permanent displacement offset after shaking (the largest offsets were of the order of only 0.1 in.).

The combination isolation system offers four important features:

1. resistance to wind loads and low-level shaking is implicit in the behavior of the slider bearings
2. a restoring effect is provided by the elastomeric bearings to eliminate displacement offsets
3. control of overturning and extreme displacements is provided
4. the slider bearings represent a fail-safe backup to the elastomeric bearings for cases of extreme loading.

3. Bridge Deck Tests

Base isolation has been implemented extensively in the seismic design of bridges. In an effort to answer some of the questions on the response of base-isolated bridge decks an experimental program[11] was initiated to address a number of issues, including the effect of the type of isolation system on the deck behavior and the response of skew isolated bridge decks. A 20-ft-long steel deck, simulating one simple span of a bridge was tested using two different isolation systems. The first consisted of high damping multilayer natural rubber bearings (8x8x7.8 in. high) with two shear dowels in each end plate and the second used natural rubber bearings of the same design but additionally incorporating 1½-in. lead plug inserts.

A parameter identification routine designed to provide an equivalent linearization of the dynamic response of the nonlinear isolation system was developed (that gave accurate displacement and acceleration maxima) to provide elementary design rules for the preliminary design of base-isolated buildings and bridges. The lead-rubber bearings were effective in reducing deck displacements 25-50% over the high damping bearings and for the real-time earthquake signals these displacement reductions were not achieved at the expense of increased accelerations. In bridge decks the higher modes are generally very much higher than the fundamental mode and unlike the case of building structures will not be excited by the lead-rubber bearings. For this reason lead-rubber bearings are highly effective for bridge structures. Other results of the test series illustrated that a very simple formula can be used to predict the roll-out displacement of a bearing system. This is important as roll out governs the displacement capacity of the isolation system and hence the system limit-state for an ultimate event.

Conclusions

The development of two static rigs has allowed detailed investigations of single isolator components to be undertaken. The effective stiffness and damping properties of isolators and the variation of these properties with amplitude and frequency can be determined. Tests of isolators can be performed to verify the accuracy of theoretical and simplified design predictions of performance parameters. The test rigs also allow the reliability and repeatability of the behavior of isolators to be evaluated.

The earthquake simulator provides the ability to perform studies of the behavior of isolation systems incorporated in large-scale structures subjected to a wide range of dynamic loadings. The studies have shown the effectiveness of base-isolation systems at reducing structure responses to earthquake motions. It has been shown that base isolation is suitable for medium-rise structures and a system to overcome the potential problem of structure uplift has been developed. Other studies have shown the particular suitability of base isolation to bridge decks and evaluated the effectiveness of the proposed SEAONC code regulations to predict the response of a range of different isolation systems for design purposes.

The ability to test base-isolation systems and individual isolation components and to demonstrate the performance of such systems to earthquake loadings is a very important step toward achieving general acceptance of the technique of base isolation as a feasible and practical seismic design strategy.

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Table 1
Results for Type-3 Bearing Tests

Test File	Signal	Span	PGA (g)	Peak Response (g)	Response / PGA	d_{max} (in.)	Shear Strain (%)	Stiffness K_h (k/in.)	ξ (%)
861013.03	sf2	150	1.065	0.186	0.175	0.67	18.8	6.35	13.5
861013.04	taft2	150	0.282	0.094	0.333	1.05	29.5	5.74	10.2
861013.05	pac2	225	0.359	0.117	0.325	1.56	43.8	5.35	10.6
861013.06	park2	225	0.257	0.122	0.474	1.67	46.9	5.09	11.0
861013.07	sf2	250	1.479	0.264	0.178	1.09	30.6	5.61	12.8
861013.08	taft2	200	0.393	0.118	0.299	1.42	39.8	5.10	10.8
861013.09	taft2	225	0.446	0.132	0.297	1.60	44.9	4.95	10.8
861013.10	ec2	200	0.405	0.178	0.440	2.41	67.6	4.42	11.9

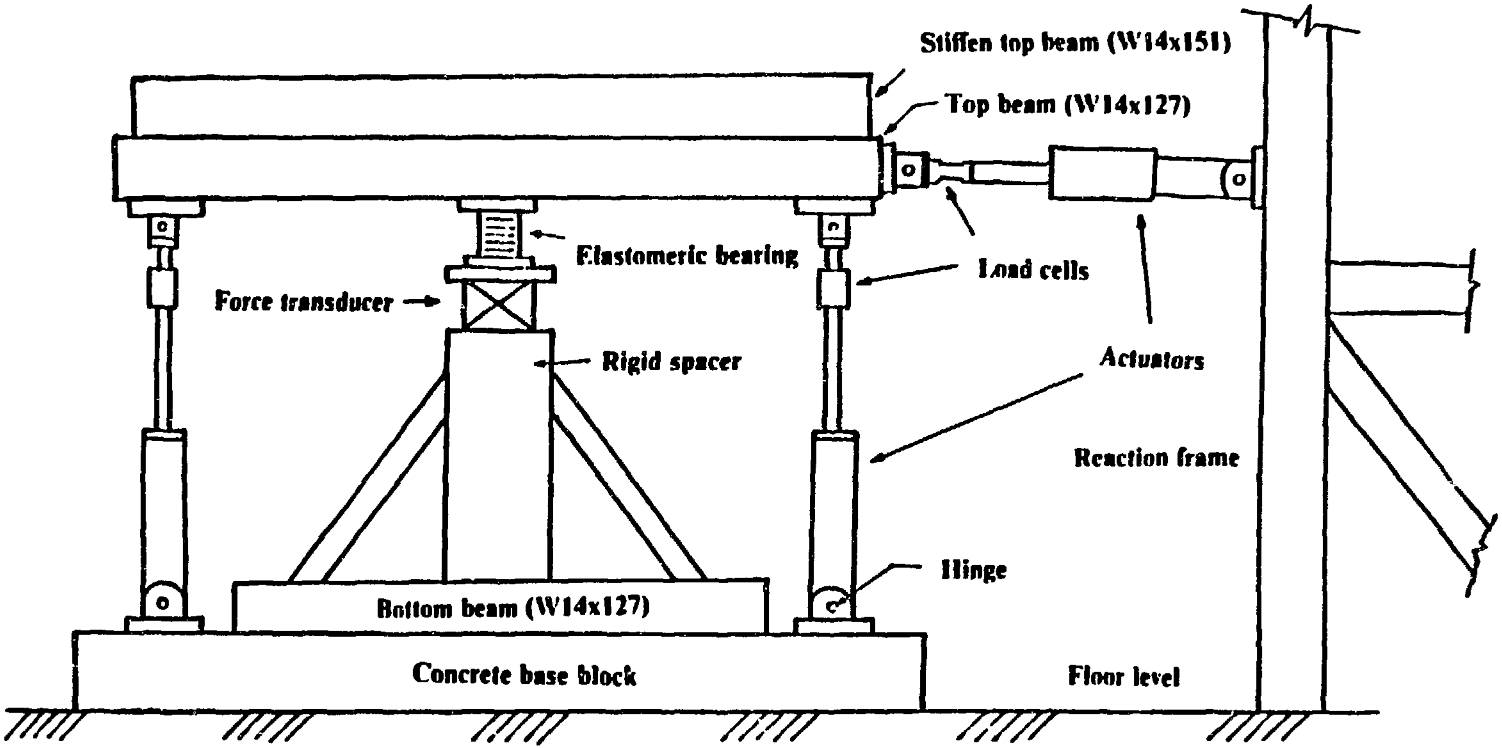


Fig. 1. Single Bearing Shear Test Rig

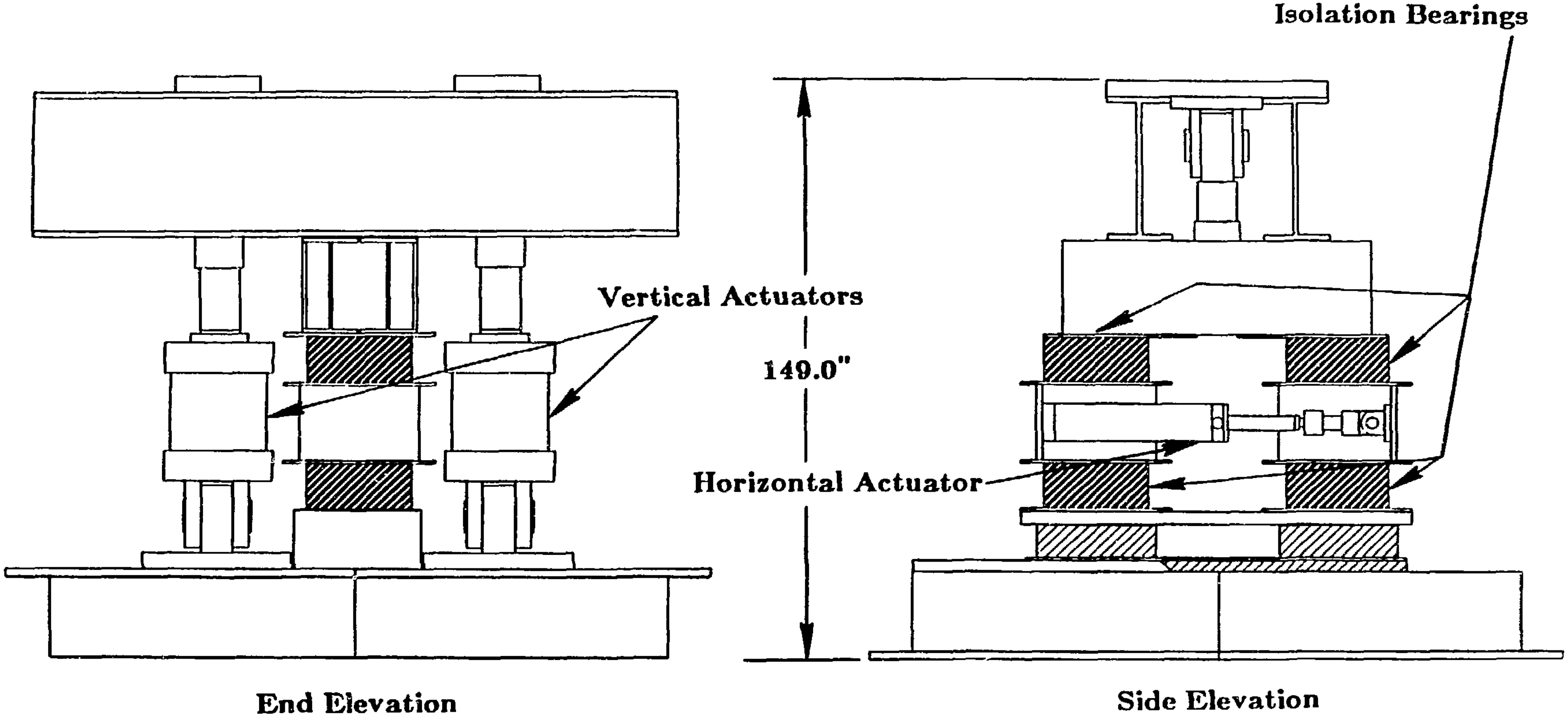


Fig. 2. Large-Scale Bearing Test Rig

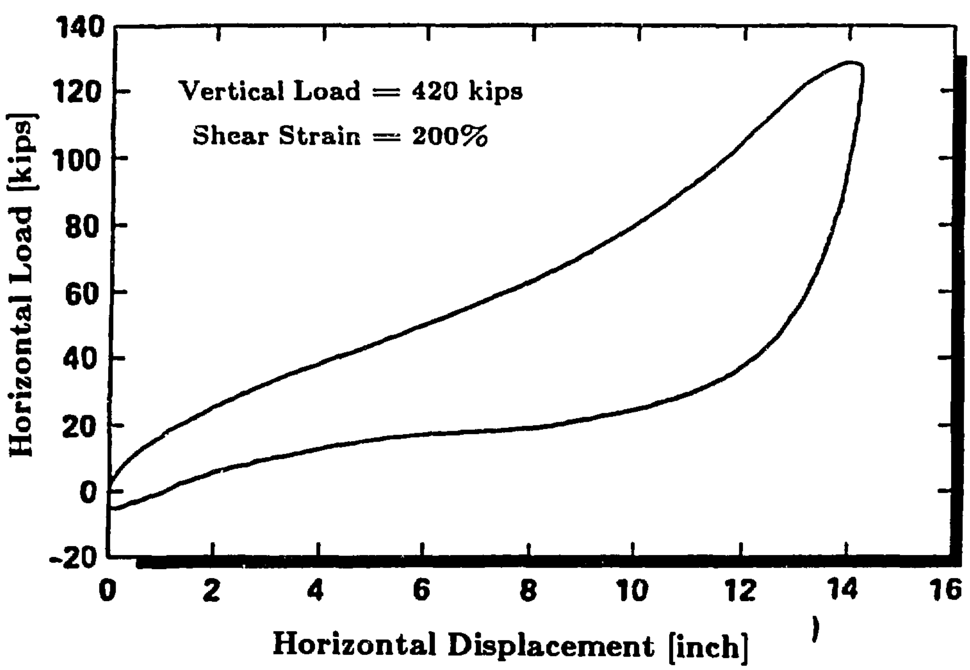


Fig. 3. Shear Force Hysteresis Behavior for Half-Size Seismic Isolator

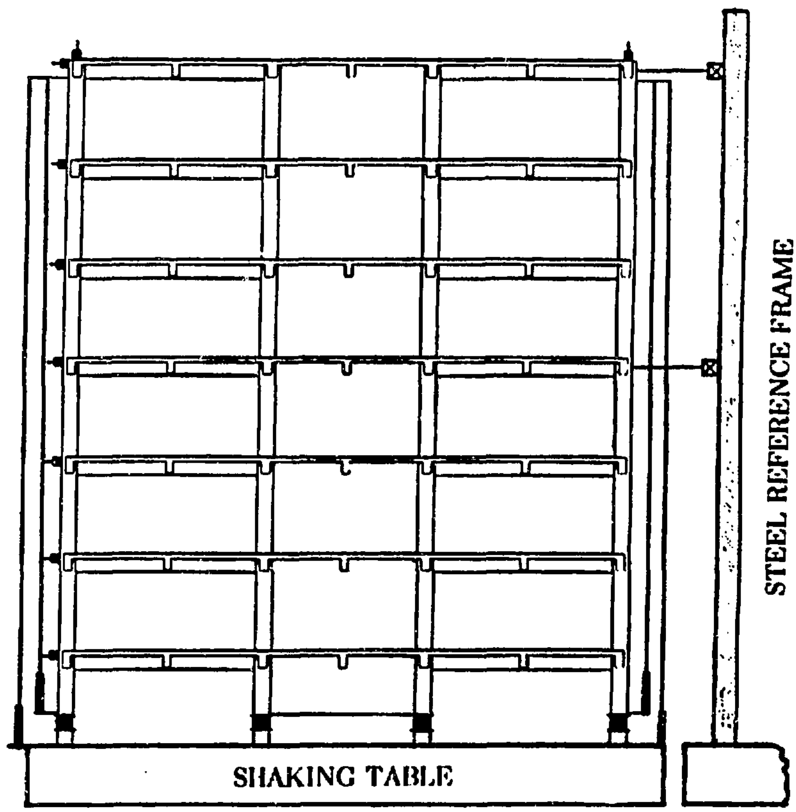


Fig. 4. 1/5-Scale Reinforced Concrete Test Structure

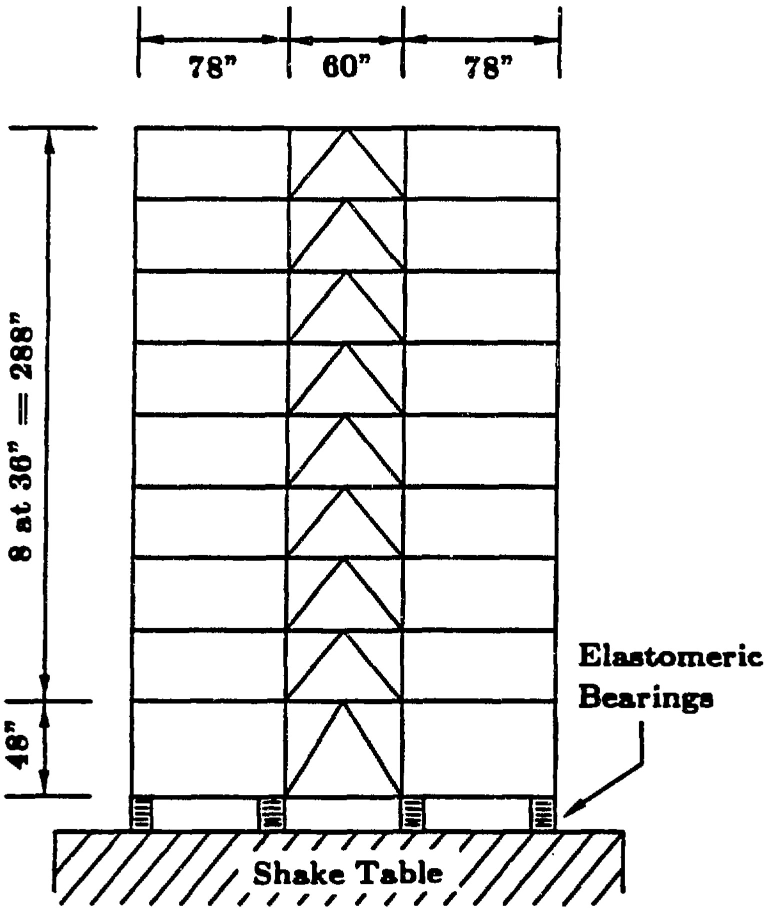
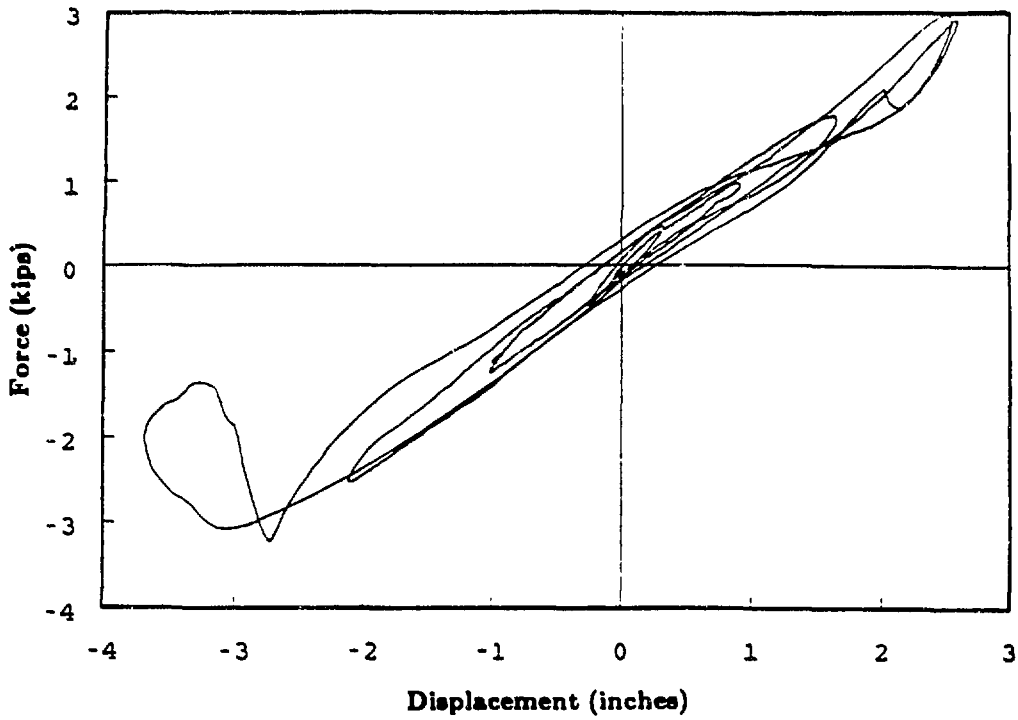
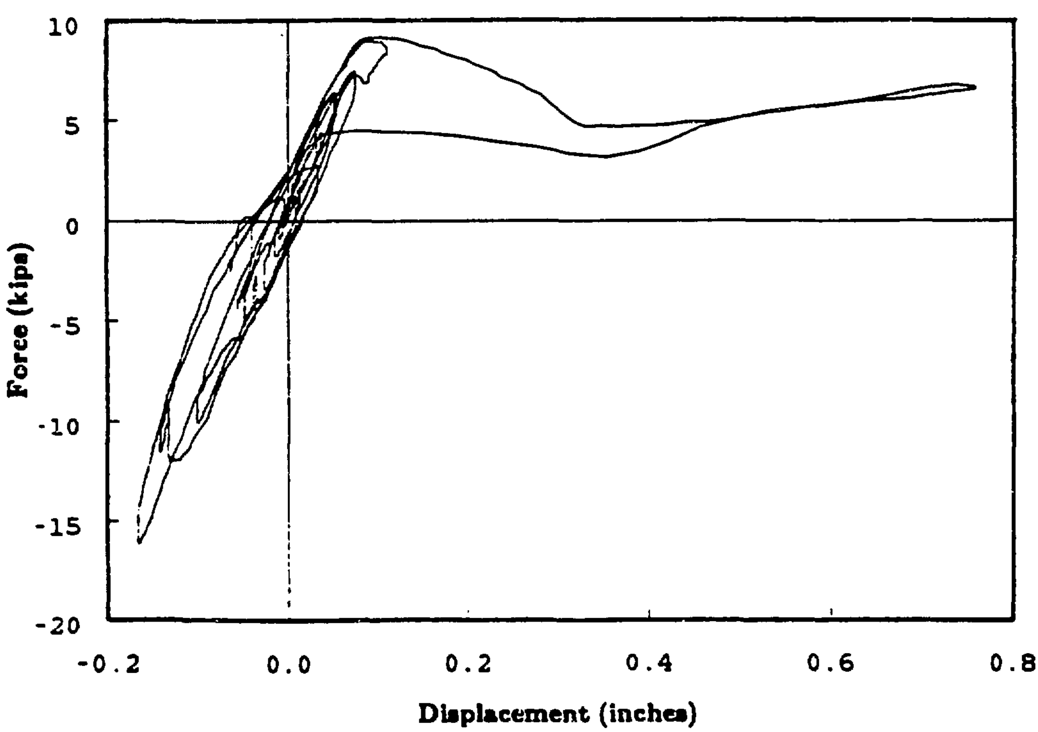


Fig. 5. 1/4-Scale Steel Test Structure

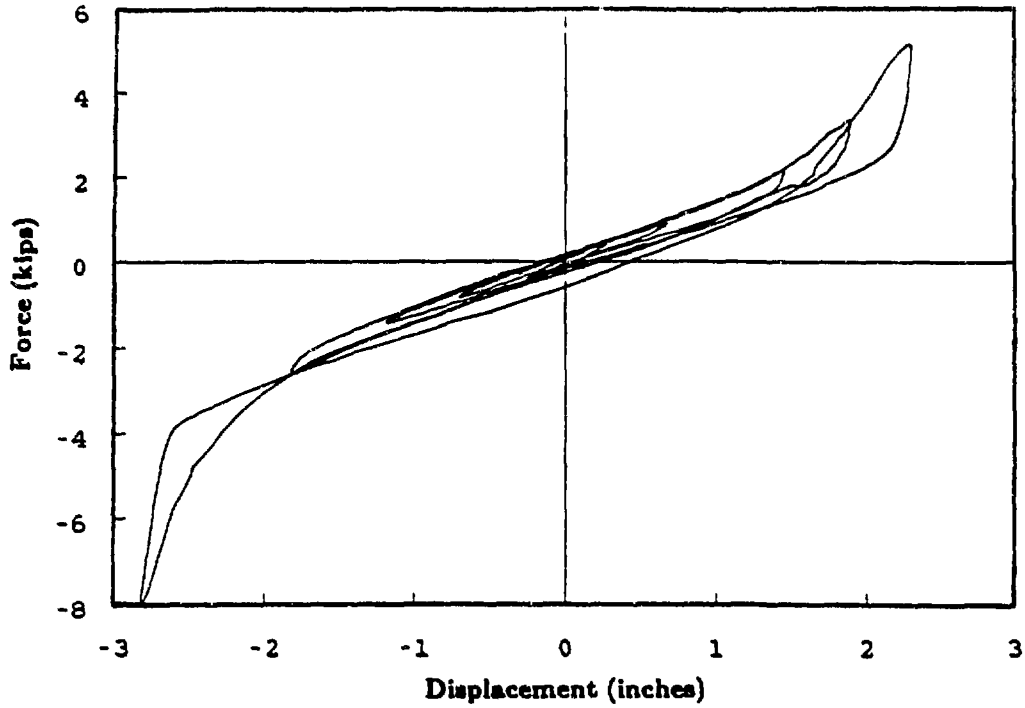


(a) Shear Force vs. Horizontal Displacement

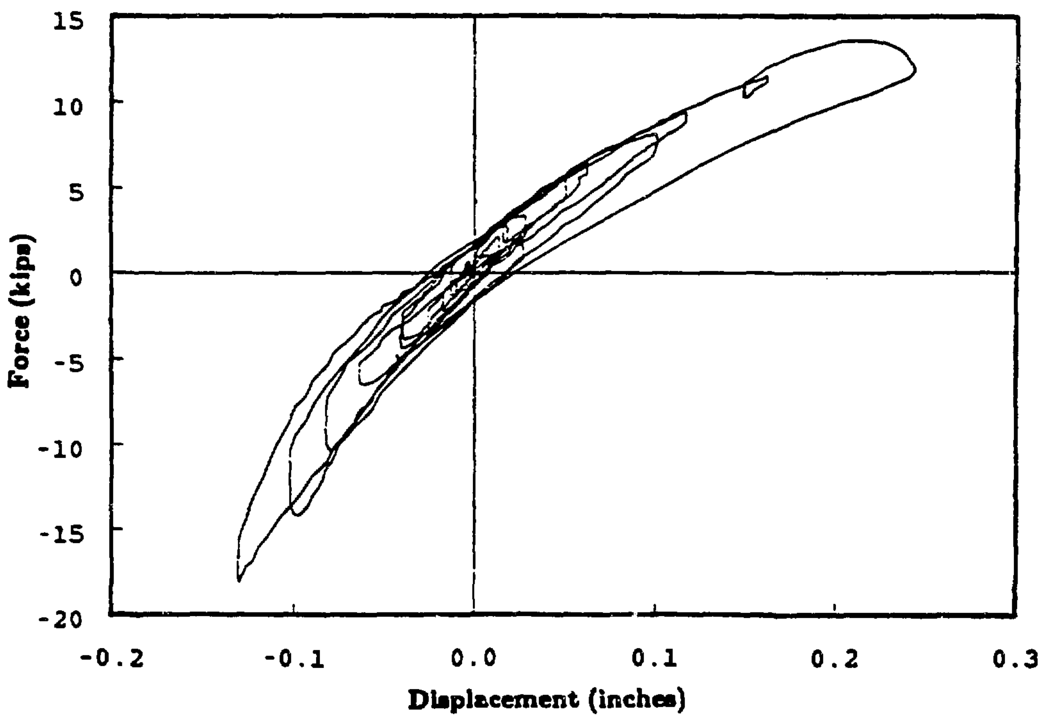


(b) Axial Force vs. Vertical Displacement

Fig. 6. Shear and Axial Force Behavior of Bearings to Free-to-Uplift Conditions



(a) Shear Force vs. Horizontal Displacement



(b) Axial Force vs. Vertical Displacement

Fig. 7. Shear and Axial Force Behavior of Bearings in Uplift-Restrained Condition

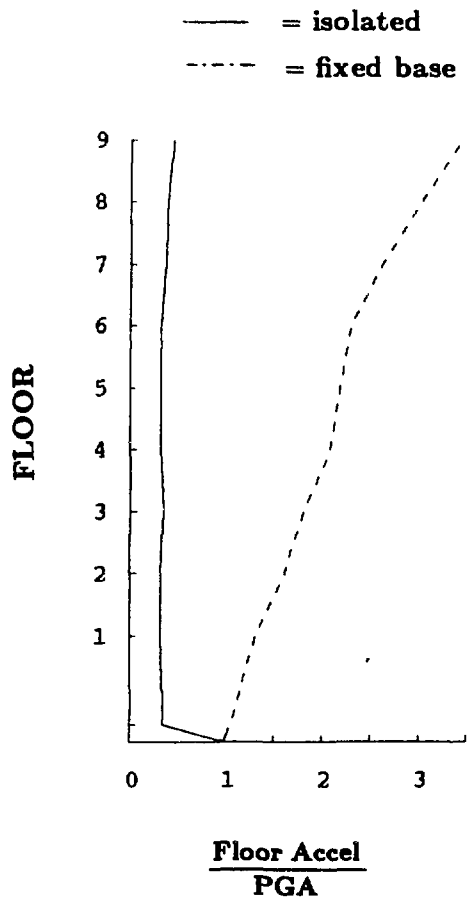


Fig. 8. Acceleration Response Profiles.
El Centro PGA = 0.405 g Test

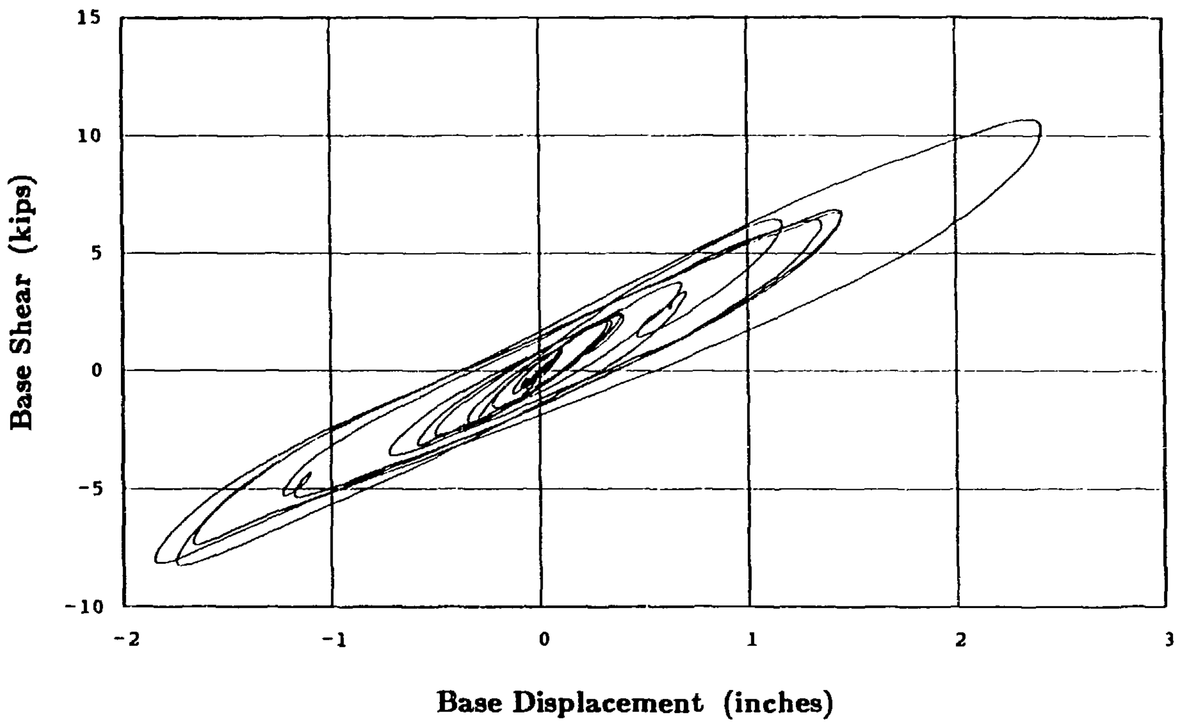


Fig. 9. Shear Hysteresis Behavior of Isolation System.
El Centro PGA = 0.405 g Test