

ELASTOMERIC BEARINGS FOR THREE-DIMENSIONAL SEISMIC ISOLATION*

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ABSTRACT

Seismic isolation offers an attractive approach for reducing seismic loads in nuclear structures, and more significantly, in reactor components. In this paper a novel isolation system which can be used in certain low rise buildings to isolate horizontal and vertical ground motions is proposed. It consists of steel-laminated elastomeric bearings which provide flexibility in both the horizontal and vertical directions by using thick rubber layers bonded to steel shim plates. An extensive testing program of scaled bearings was carried, and in general it was confirmed that it would be feasible to use such bearings to isolate stiff buildings with low center of gravity in both the horizontal and vertical directions.

INTRODUCTION

In recent years, several systems for seismic isolation of buildings have been proposed and implemented [Kelly, 1986]. Today there are over 125 structures worldwide which are isolated and the numbers have been increasing steadily in the last few years. This is especially true in Japan, where since 1982, over 20 seismically isolated buildings have been constructed [Kelly, 1988], and another 16 have received construction permits [Kitagawa, 1989]. The majority of these systems use steel-laminated elastomeric bearings to isolate the building and its contents from the horizontal components of the earthquake ground movement. Elastomeric bearings can be designed to provide a wide range of vertical stiffness and horizontal stiffness. In general elastomeric bearings have been designed to be very stiff in the vertical direction such that the vertical components of the earthquake are transmitted through the foundation to the structure relatively unchanged.

In certain cases a double isolation system has been used where the building is isolated in the horizontal direction and only equipment that are sensitive to vertical motions are isolated locally in the vertical direction. An example of this

approach is the High Technology Research Laboratory building in Tsukuba Japan, which is isolated in the horizontal direction using steel laminated elastomeric bearings and steel bar dampers, and air springs are used to isolate an electron microscope in the vertical direction [Ohbayashi Corp., 1988]. The effectiveness of this design both in isolation of ambient vibrations as well as seismic motions has been demonstrated. A similar approach has been proposed in the conceptual design of a large 1500 MWe liquid metal fast breeder reactor (LMFBR), the Superphenix 2 in France. The entire nuclear island is isolated in the horizontal direction using elastomeric pads and viscous dampers, and additionally, the reactor cavity is isolated in the vertical direction using helical steel springs and viscous dampers [Feuillade and Richard, 1986].

Systems which are flexible in the horizontal as well as in the vertical direction have also been proposed for three-dimensional (3-D) isolation of buildings. One such system, which consists of large blocks of unreinforced natural rubber, was used to isolate a school building in Skopje, Yugoslavia [Siegenthaler, 1970]. Although additional development work was carried out on this system including shake table tests [Staudacher, 1984], it has not been implemented in other buildings. Another proposed system for 3-D seismic isolation of buildings uses large steel helical springs and visco-dampers commonly used for vibration isolation of large machine foundations [Huffmann, 1985]. In both these systems, the vertical stiffness is close to the horizontal stiffness. Thus when they are used to isolate buildings the horizontal and rocking response will be coupled resulting in large vertical accelerations at the corners of the building even in the presence of input which is purely horizontal and the possibility of liftoff of the isolators.

For buildings of low aspect ratio (height to width ratio less than two), and with a low center of gravity, the concept of (3-D) isolation becomes practical as the concern for overturning and uplifting can be considerably lessened. This concept can be especially useful for buildings or structures which house equipment that are sensitive to vertical motion

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such as electronic equipment and some nuclear reactor components. In this paper, a novel isolation system which can be used for 3-D isolation of such buildings is proposed. It uses steel-laminated elastomeric bearings with thick layers of rubber that provide flexibility in the horizontal direction and some flexibility in the vertical direction. These bearings have the added advantage that they would isolate the building and contents from ambient ground vibrations, and they could be more easily removed for inspection by compressing the bearing.

A design using this approach was developed for an Advanced Liquid Metal Reactor (LMR) building concept, the Sodium Advanced Fast Reactor (SAFR). SAFR was supported by the U.S. Department of Energy (DOE) and was being developed by a team led by Rockwell International. Support for this program was terminated in 1989.

A series of tests were performed on prototype quarter-scale SAFR bearings at the Earthquake Engineering Research Center (EERC) of the University of California in Richmond, California to examine the feasibility of using the proposed bearings for 3-D isolation of nuclear buildings, and to verify the applicability of existing design formulas. The results and main conclusions of the testing program are summarized below.

DESCRIPTION OF THE SAFR DESIGN

SAFR employs a 450 MWe pool type LMR as its basic module. The reactor assembly module is a standardized shop-fabricated unit housed in a building constructed above grade with plan dimensions of 124 ft. by 82 ft. [Oldenkamp et al., 1988] as shown in Figure 1. The total weight of the reactor building and its contents is 63,000 kips. Seismic isolation was incorporated in the SAFR reference design to support plant standardization, enhance plant safety margins, permit siting in zones with higher seismicity, and potentially reduce plant costs.

The building is supported on 100 steel-laminated elastomeric bearings which provide both horizontal and vertical isolation. The design horizontal frequency is 0.5 Hz and the vertical frequency is 3 Hz. The low vertical frequency is achieved by using bearings with thicker rubber layers bonded to fewer steel shims. Such bearings are referred to as low shape factor (LSF) bearings where the shape factor, S , is defined as the compressive area divided by the area free to bulge for a single layer. For circular bearings S becomes,

$$S = \frac{D'}{4t}$$

where D' is the steel shim diameter and t is the thickness of a single rubber layer.

To date, interest in low shape factor (LSF) bearings has been mainly for the development of isolation systems that can isolate buildings from horizontal earthquake loading as well as ambient ground vibrations (horizontal plus vertical). In Japan, Kajima Corporation has demonstrated the effectiveness of such systems by constructing an acoustic laboratory on LSF bearings [Koshida et al., 1989] with a horizontal frequency of 0.5 Hz and a vertical frequency of 5 Hz. Analysis, vibration testing, and recorded earthquake data have demonstrated the advantages of this system.

The SAFR bearings have a diameter of 42 in., a total height of 16.25 in., and consist of three layers of rubber each 4 in. thick separated by two 1/8 in. steel shims resulting in a shape factor of 2.3. In contrast, elastomeric bearings which

are stiff vertically have shape factors which exceed 15. The required design bearing horizontal and vertical stiffnesses are 16.1 kip/in and 580 kip/in, respectively.

The seismic design basis is a design safe shutdown earthquake (SSE) with a maximum horizontal and vertical acceleration of 0.3 g anchored to a design earthquake that envelopes the NRC Regulatory Guide 1.60 spectra. The selected criteria are expected to cover over 80 percent of potential nuclear sites in the U.S. excluding California. Options for siting in higher seismic zones, with design earthquakes exceeding 0.5 g, were investigated and were found acceptable.

RESULTS OF SEISMIC ANALYSIS

Dynamic analyses were performed to compare the response of SAFR with and without isolation. A comparison of horizontal and vertical response spectra at the reactor supports is shown in Figure 2. It can be seen that there are substantial reductions in horizontal accelerations at all the equipment resonant frequencies. In the vertical direction, the response is amplified at the vertical isolation frequencies, but is reduced at frequencies greater than 4 Hz which is the range of equipment vertical frequencies. The maximum SSE horizontal displacement of the bearings was computed to be 9 in. In general, a large amount of rocking will result in buildings supported on such bearings. However, because of the low center of gravity of the SAFR building and its wide base only a small amount of uplift due to rocking was computed in the corner bearings.

SEISMIC ISOLATOR TESTS

It was recognized from the onset of this program that bearing tests would have to be performed to demonstrate the feasibility of using LSF bearings and to verify the validity of design equations. An extensive experimental program was undertaken at EERC to investigate the performance characteristics of the SAFR LSF bearings. The test series had the following objectives:

- Evaluation of vertical stiffness
- Evaluation of horizontal stiffness and damping, and the influence of vertical load on these characteristics
- Identification of failure modes under axial load and combined axial and shear
- Investigation of the effect of end plate connection on the performance and stability of bearings under extreme loads.

Six quarter-scale bearings were tested (see Table 1 for dimensions). Two types of bearing to foundation connections were considered: a dowel type connection, and a rigidly bolted type connection (see Figure 3). Additionally, two types of natural rubber compound: a filled (high-damping) rubber and a conventional unfilled rubber were investigated.

A total of 265 nondestructive tests were performed on the bearings followed by failure tests. Each bearing was tested individually in the test fixture shown in Figure 4. The fixture is capable of applying horizontal displacements of ± 6 in. at a maximum velocity of 30.0 in/sec or 10 in. in any one direction. In this paper, due to space limitations, only the results for the unfilled rubber bearings are presented. The high damping bearing results will be reported elsewhere. The bolted bearing will be referred to as LB and the dowelled as LD.

TEST RESULTS

Vertical Tests

A series of vertical tests were performed in which each bearing was loaded monotonically from zero load to peak loads of 15.9, 31.8, 47.7, and 63.6 kips and back to zero load. The cyclic vertical stiffness around an initial vertical load, which is more relevant from the design point of view, was also measured for four initial axial load levels and are shown superimposed on the 63.6 kips monotonic test in Figure 5. The vertical stiffness was observed to increase with increasing vertical load, however, at a much smaller rate than was observed for previously tested high shape factor bearings [Kelly et al., 1990]. The ratio of cyclic to monotonic stiffness for the four axial load levels was computed. For the design level load (7 percent axial prestrain), there is about a 15 percent increase in vertical stiffness. The full-scale vertical stiffness based on extrapolation of measured values at the design vertical load is 588 kip/in which compares well with the design target value of 580 kip/in.

The effect of horizontal displacement offset on cyclic vertical stiffness was also examined. In general there was a slight increase in stiffness with increasing strain level. For example, the increase in vertical stiffness between zero offset and 1.5 in. offset (50 percent shear strain) was only 5 percent.

The equivalent viscous damping coefficient was evaluated from the vertical hysteresis loops and was found to exceed 17 percent for the unfilled rubber compound. The damping was essentially independent of the horizontal offset and amplitude of the applied vertical load. The measured damping exceeds the damping used in the analysis which was limited to 10 percent. A comparison of bolted and dowelled bearing results showed that the end plate connection detail had no influence on the vertical stiffness and damping.

Horizontal Tests

A series of tests were performed in which each bearing was subjected to five cycles of horizontal load at 0.75 Hz to constant values of peak shear strain ranging from 10 to 160 percent while maintaining a constant vertical load. Four levels of axial load were applied, 15.9, 31.8, 47.7, and 63.6 kips. The hysteresis loops for the design axial load of 31.8 kips for the LD bearing are superimposed for different strain levels in Figure 6 and the loops at 160 percent strain for the four axial load levels are superimposed in Figure 7. The horizontal stiffness as a function of shear strain for different axial load levels is shown in Figure 8. It can be seen that the horizontal stiffness is high at low strains and decreases at higher strains but is fairly constant above 40 percent strain. Additionally, the bolted bearing horizontal stiffness is not sensitive to vertical load. This is in contrast to the results obtained from the dowelled bearings, where the stiffness was observed to be highly sensitive to vertical load.

The equivalent viscous damping ratio in the horizontal direction for the design level axial load and 50 percent shear strain the damping was computed to be about 5.5 percent. The damping was observed to be more sensitive than horizontal stiffness to axial loads and increased significantly at higher axial loads especially for the dowelled bearings. This type of behavior has also been observed in tests of bearings with high shape factors which showed that as the applied axial load tended to the bearing buckling load, the damping of the bearing increased [Koh and Kelly, 1987].

Shear Failure Tests

A series of large shear strain tests were performed on the bolted and dowelled bearings. The objective of these tests was to fail a bearing in shear while subjected to a constant vertical load. An initial loading cycle of 50 percent strain was performed to determine the stiffness of the bearings prior to any degradation. The axial load during these tests was 31.8 kips. Subsequently the bolted bearings were deformed horizontally to maximum strains corresponding to 200, 225, 328, and 344 percent. The force displacement plots for these tests are shown in Figure 9. A photograph of the bearing at 330 percent strain is shown in Figure 10. The first evidence of failure was seen during the 328 percent strain test, where, at approximately 9.5 in. (320 percent strain) a change in stiffness was observed. This coincided with tearing of the bottom elastomer layer. It should be noted that the subsequent 344 percent strain test revealed only a small loss of stiffness beyond about 4 in. of displacement, and even though the bearing was failed in the previous test, it was capable of accommodating loads in excess of that at which significant damage to the bearing had first occurred. In fact, after the bearing had totally failed and it was forced back to its original position, it showed no signs of distress when the 50 percent test was repeated. This finding implies that current acceptance test specifications which require that bearings be tested up to 100 percent shear under the design axial load will not be capable of detecting potential defects in the bearings. Thus as part of acceptance tests, it would be important to shear the bearings under the minimum axial load possible.

Another important observation is that as previously observed in high shape factor bearing tests [Tajirian et al., 1990], the horizontal stiffness of bolted bearings increases appreciably at shear strains greater than 150 percent thus providing an inherent mechanism for limiting displacements during extreme events.

Large displacement shear tests were also performed on the dowelled bearing to investigate geometric instability or roll-out. These tests were performed for various axial load levels and peak strain levels of 100, 200, and 263 percent, and ending with repetition of the 100 percent test. Figure 9-b shows the force-displacement relationship for an axial load of 31.8 kips. Roll-out (disengagement of the dowels) occurred in this case around 7 to 7.5 in. or about 250 percent strain. As can be seen in Figure 11 that even after the initiation of roll-out, the bearing continues to provide resistance. This is partly due to the fact that the bearing is flexible in the horizontal direction, and it tends to roll in the available confined space. The test was repeated for an axial load of 15.9 kips and roll-out once again occurred at around 7 in. The 50 percent tests performed prior to and following both roll-out tests showed that there was negligible loss of stiffness even after the bearing and its internal plates underwent extreme shape distortions. The stiffening effects observed in the bolted tests were not as pronounced in these tests.

The extrapolation of these results to full-scale bearings show that they would be capable of accommodating 38 in. of horizontal displacement in the bolted configuration and 28 in. in the dowelled configuration. This means that there would be a margin of 4 for the design earthquake of 0.3 g for the bolted case, and a margin of 3.1 for the dowelled case.

Loading Frequency Effects

Tests to investigate the effects of loading frequency on the bearing stiffness and damping were performed for hori-

zontal and vertical loading conditions. In general, it was observed that rate effects were small and that variations due to other factors masked any rate-related trends.

Tension Failure Tests

Pure tensile tests were performed on a high-damping bolted bearing to determine the uplift capability of LSF bearings. The first set of tests consisted of full cycles of tension-compression loading at increasing amplitudes. The axial load-vertical displacement plots for these tests are shown overlain in Figure 11. As to be expected there is a noticeable difference between the tensile and compressive stiffness. While the tensile stiffness corresponds to the tensile stiffness of the elastomer, the compression stiffness is influenced by additional factors such as the shape factor.

The remaining tests consisted of half-cycles of tensile load applied until failure was induced. The tensile load vertical displacement plots are shown in Figure 12. The highest load reached was 31.4 kips. Visible tearing of the top rubber layer of the bearing was observed during the later stages of this loading cycle. However, even with initiation of failure, subsequent tests showed that the bearings were capable of sustaining a peak tensile load of 22 kips. The ultimate tensile stress based on the shim plan dimensions was about 500 psi.

CONCLUSIONS

Dynamic tests performed on reduced scale low snape factor (LSF) steel-laminated elastomeric bearings confirmed the feasibility of using such bearings for horizontal and vertical seismic isolation of certain types of buildings such as the SAFR LMR power plant building. The tests demonstrated that it is possible to design bearings that have the necessary horizontal and vertical stiffness to achieve 3-D isolation. Furthermore, the bearings are capable of accommodating extreme horizontal displacements with margins four times the displacements computed for the SSE level earthquake. Bolted bearings are preferable to dowelled connections because they can accommodate larger horizontal displacements and remain stable even under very low axial loads. Furthermore, the vertical and horizontal stiffness for such a configuration is independent of the axial load in the range of the applicable design load. Additionally, the horizontal stiffness of bolted bearings increases substantially at high shear strain levels providing an inherent mechanism for limiting displacements during extreme events. Tensile tests demonstrated the capability of bolted bearings in providing resistance against uplift. No damage or degradation of bearing mechanical properties was observed even after several cycles of extreme loading which resulted in severe distortions of the bearing geometries. To further proof this design, it would be necessary to perform tests on larger scale bearings, as well as shake table experiments to verify system response. Finally when using bolted bearings it is essential to demonstrate that high quality bearings can be manufactured where ultimate failure always occurs due to rupture of the elastomer and not bond failure.

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Table 1 Comparison of SAFR Bearing Properties

	Full Scale	Quarter Scale
Outside diameter (in.)	42	10
Thickness of end plates (in.)	2	1
Number of rubber layers	3	3
Thickness of rubber layers (in.)	4	1
Number of steel shim plates	2	2
Thickness of shim plates (in.)	0.125	0.105
Diameter of shim plate (in.)	38	9
Total bearing height (in.)	16.25	5.21
Shape Factor	2.4	2.3
Design vertical load (kips)	630	31.8
Design pressure (psi)	455	405

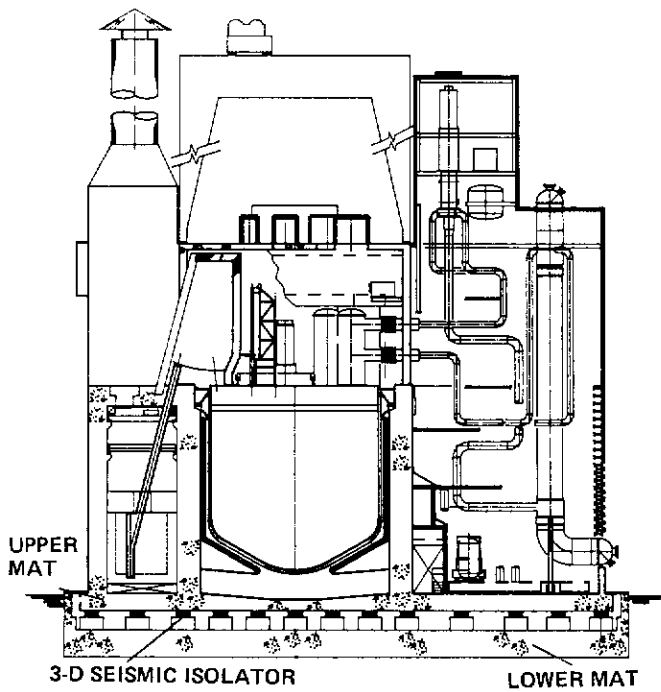
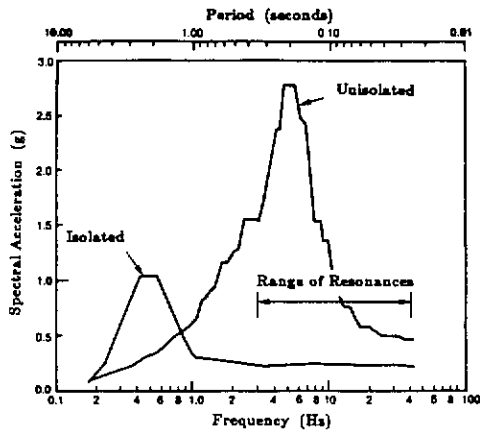
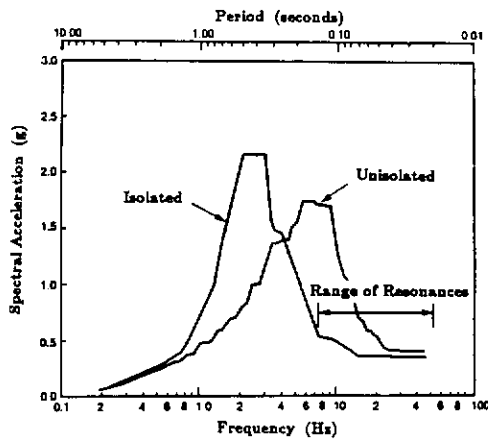


Fig. 1 Section of SAFR Plant

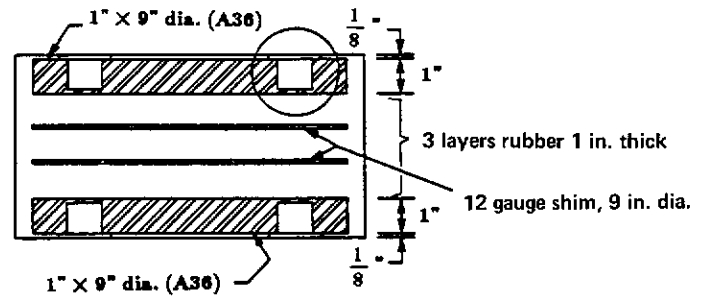


(a) Horizontal Direction

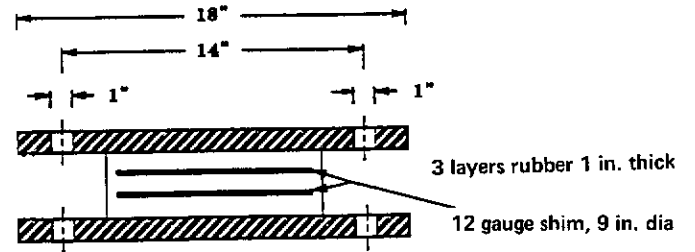


(b) Vertical Direction

Fig. 2 Comparison of SAFR Response Spectra



(a) Dowelled (LD) Bearing



(b) Bolted (LB) Bearing

Fig. 3 Typical Quarter-Scale LSF Bearing

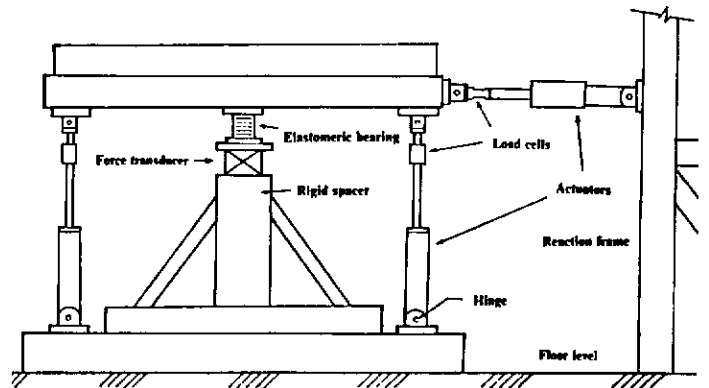


Fig. 4 EERC Single Bearing Test Machine

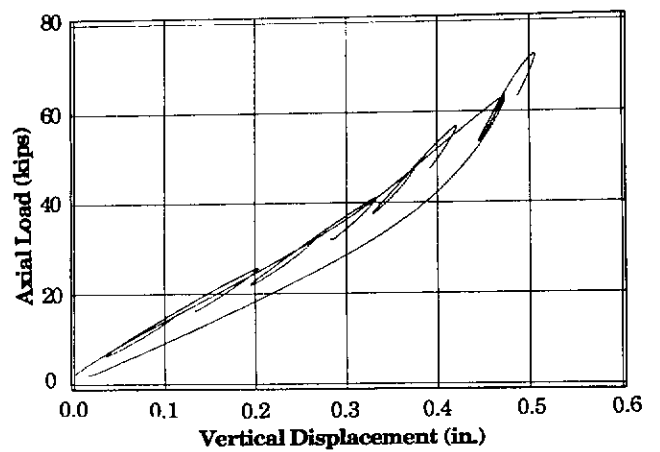
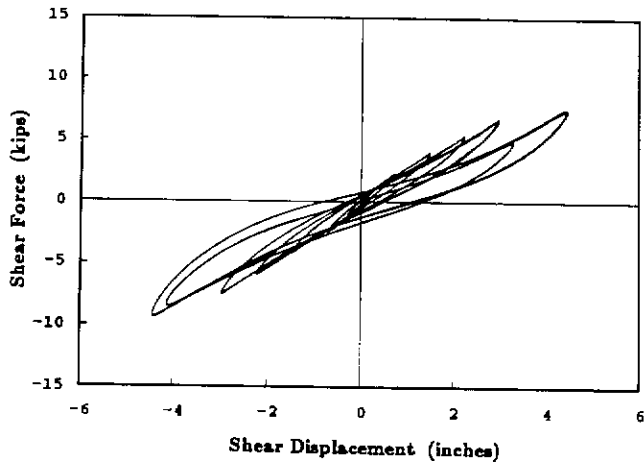
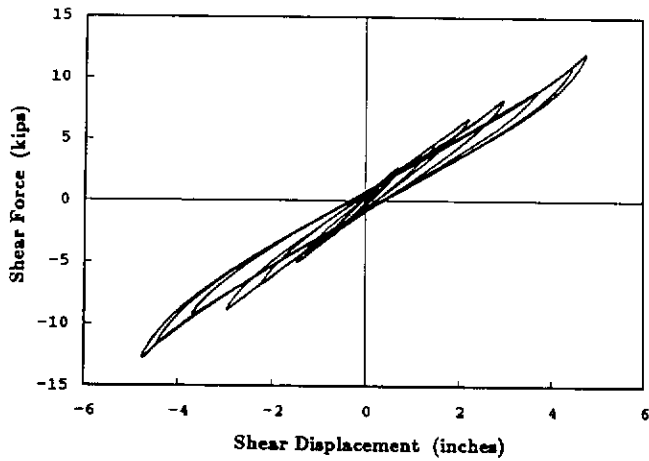


Fig. 5 Cyclic Vertical Loading Superimposed on Monotonic Vertical Loop for Axial Load = 61 kip, LB Bearing



(a) LD Bearing



(b) LB Bearing

Fig. 6 Hysteresis Loops for Cyclic Shear Tests, Constant Axial Load = 31.8 kips

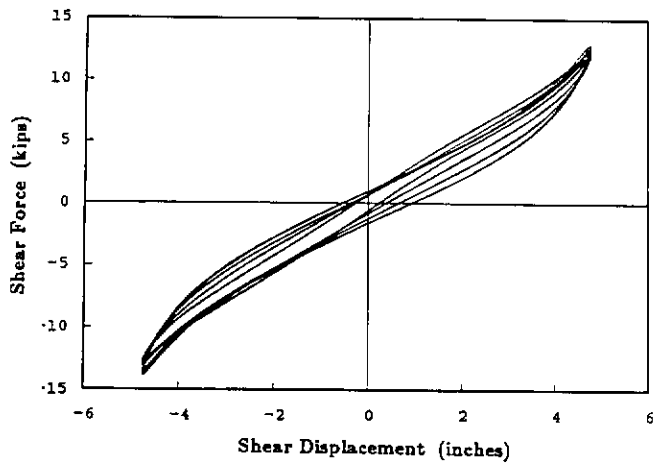


Fig. 7 Hysteresis Loops for Cyclic Shear Tests, Four Axial Loads, Constant 160% Shear Strain

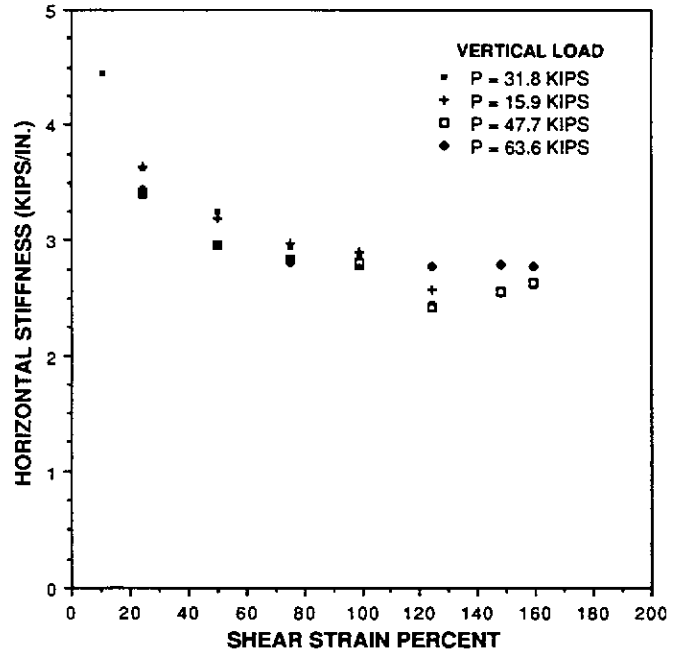
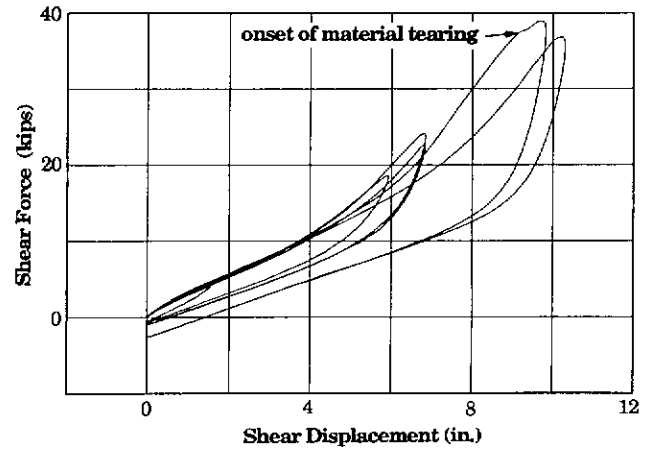
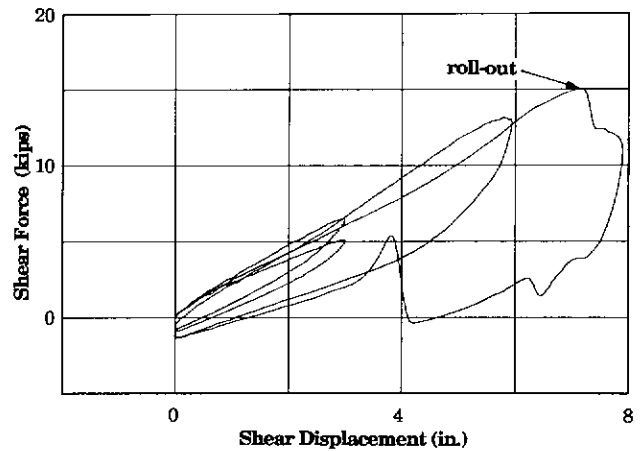


Fig. 8 Effective Horizontal Stiffness vs. Shear Strain, LB Bearing



(a) LB Bearing



(b) LD Bearing

Fig. 9 Shear Force vs. Horizontal Displacement, Failure Test, Constant Axial Load = 31.8 kips



Fig. 10 LB Bearing at 330 Percent Shear Strain During Failure Test

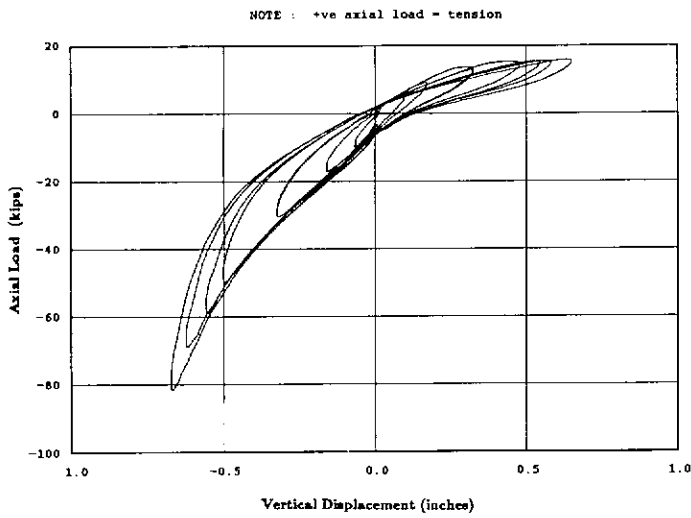


Fig. 11 Tension-Compression Load vs Axial Displacement Test, LB Bearing

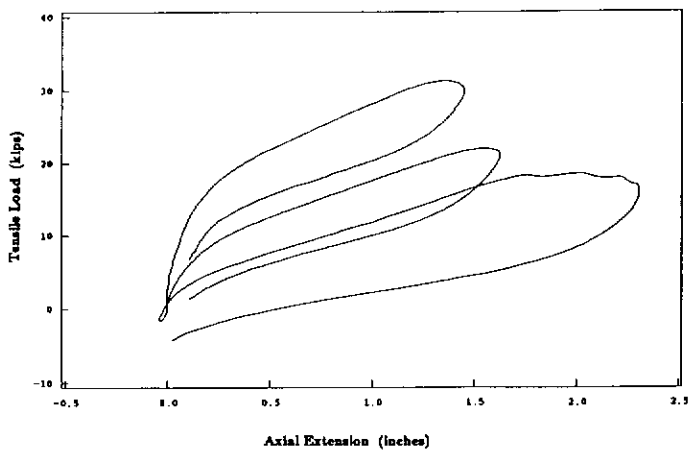


Fig.12 Tension vs Axial Displacement, Failure Test, LB Bearing