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Experimental studies of the mechanical characteristics of three types of seismic isolation bearings

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ABSTRACT: The results of an extensive series of experimental tests to identify the mechanical characteristics of three types of seismic isolation bearings are presented. Two types of high-damping rubber bearings and one type of lead-rubber bearing were studied. Cyclic horizontal displacement tests, varying the test parameters of shear displacement amplitude, axial load, and loading frequency were performed on all of the bearings. Bearing shear stiffness and damping properties were investigated in terms of the different test parameters. Ultimate-level tests consisted of monotonic shear loading to failure at several different axial loads, and tension failure tests of the bearings with bolted connections. Roll-out instability tests of the doweled bearings were conducted. Comparisons are made between experimental results and available analytical relationships for material and bearing properties.

1 INTRODUCTION

Elastomeric bearings are now the most commonly-used type of system for seismic isolation. Accurately characterizing bearing mechanical properties is a very important aspect of the design process for an isolation system, and this experimental program was aimed at confirming and refining existing analytical models for this purpose.

An extensive series of tests of three types of seismic isolation bearings was carried out with the objective of fully identifying their mechanical characteristics. Two types of high-damping rubber bearings and one type of lead-rubber bearing were studied.

The three types of bearings tested in this program were developed for earthquake simulator tests of a large-scale, reinforced-concrete model of a three-story building located in Sendai, Japan (Saruta et al., 1988, and Kelly et al., 1992). The full-size building was constructed to study the behavior of different isolation systems under real earthquake excitations. Since its completion in 1985, several different systems have been installed under the building. These have included the two types of high-damping bearings studied in this investigation. (At this time, there are no plans for the lead-rubber system to be installed).

2 BEARING DESIGNS

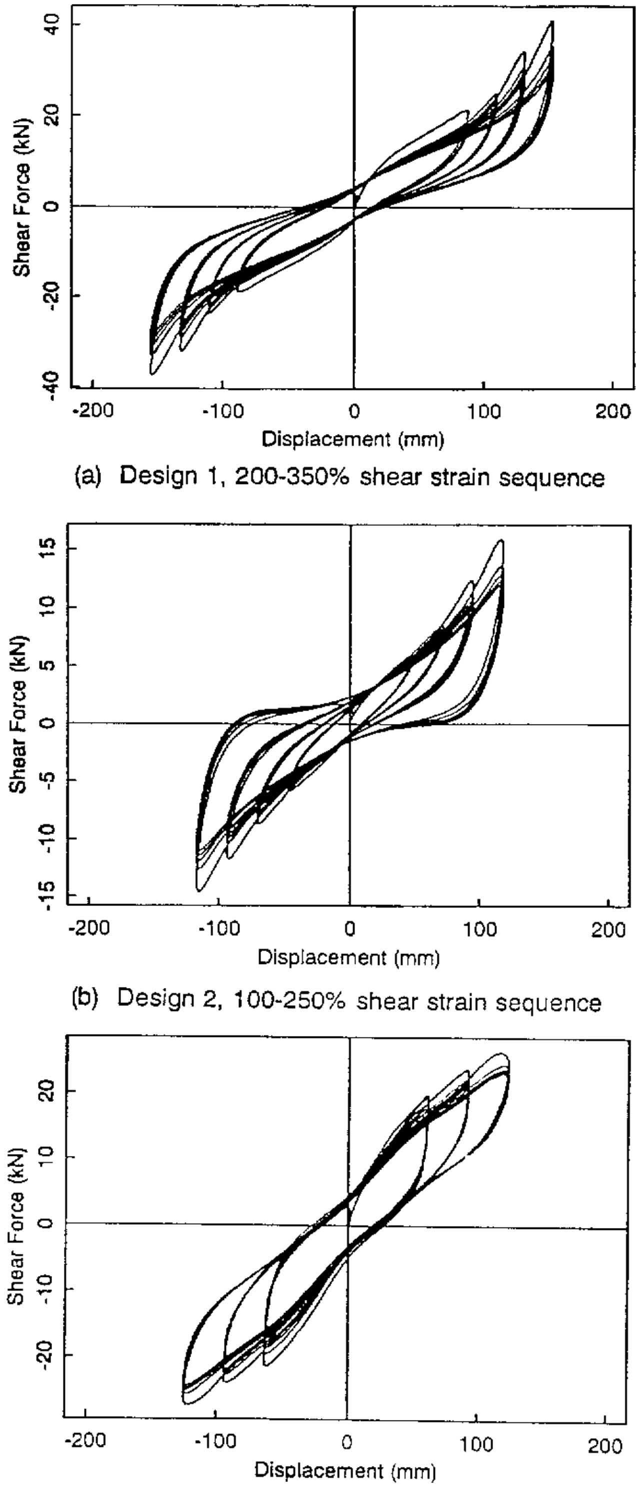
The high-damping A and high-damping B designs described below are both reduced-scale designs of the bearings that have already been installed under the full-size building. The model constructed for the earthquake simulator tests has a (geometric) scale factor of 2.5, and this is the scale factor that was used to determine the size of the reduced-scale bearings. Lead-rubber bearings have not been installed under the full-size building. With no initial bearing design to scale, the design basis for the lead-rubber bearings was selected as providing a bearing with the same stiffness characteristics as the high-damping A bearings.

The reduced-scale bearings under the model structure are subjected to axial loads of approximately 49.0 kN and 78.5 kN. These loads were the basis for defining the axial loads used in this study. With a few exceptions, only the results for the 78.5 kN tests are presented and discussed in this paper.

The designs of the 1/2.5-scale bearings are described in the following sections.

2.1 *Design 1: High-damping A*

These bearings were made from a blend of filled natural rubber and a synthetic rubber. The compound is called KL301 by the manufacturer, Bridgestone Corporation, Ltd., Japan, and is one of a suite of high-damping elastomers that they have developed for seismic isolation applications. KL301 has a shear modulus of about 4300 kPa at very small strains, which decreases to 650 kPa at 50 percent strain, 430 kPa at 100 percent strain, and 340 kPa at 150 percent strain. The bearings consist of twenty layers of 2.2 mm thick rubber at 176 mm diameter (shape factor =



(a) Design 1, 200-350% shear strain sequence

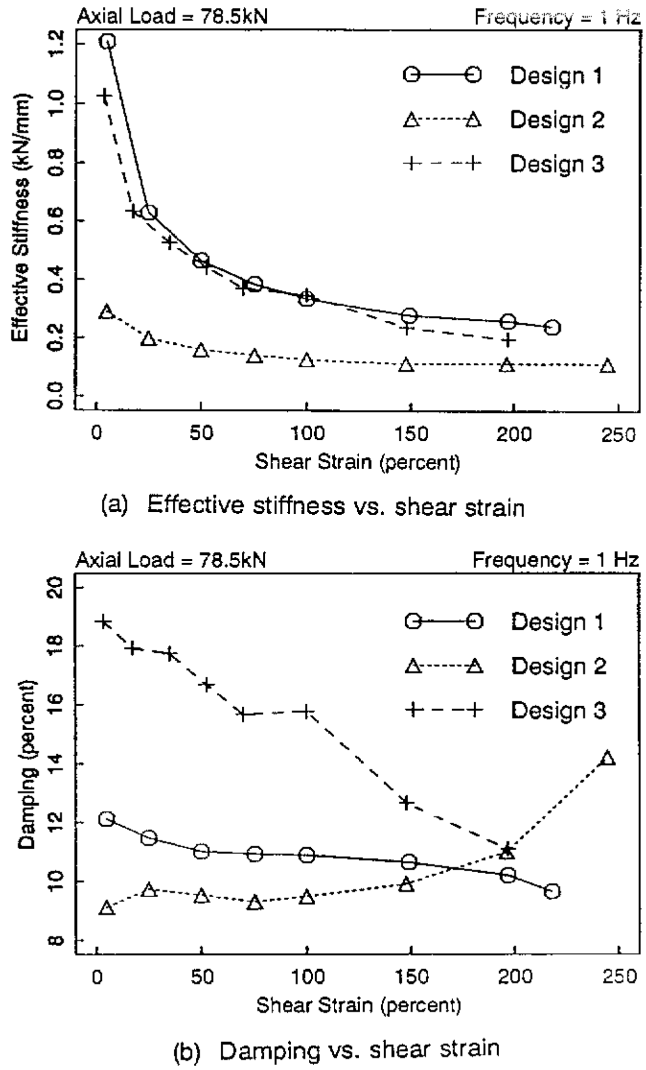
(b) Design 2, 100-250% shear strain sequence

(c) Design 3, 100-200% shear strain sequence

Fig. 4 Shear force-displacement hysteresis loops

percent at small strains, about 16 percent at 100 percent shear strain, and reducing to about 11 percent at 200 percent strain.

The manufacturer's curves for the shear modulus of the KL301 compound used in the high-damping A bearings was compared with the experimental stiffness-strain relationship of Figure 5(a). Reasonable agreement was obtained, although the predicted bearing stiffness slightly underestimated the observed stiffness. A similar comparison of predicted and measured damping ratio-strain relationships did not show



(a) Effective stiffness vs. shear strain

(b) Damping vs. shear strain

Fig. 5 Bearing stiffness and damping, all three designs

close agreement. It is believed that the reason for the difference is that the manufacturer uses a different definition than that used here for the calculation of the damping ratio from the measured data (Kelly, 1991).

Experimental force-displacement relationships for the design 3 bearings were compared with a set of design equations for lead-rubber bearings (Ministry of Works and Development, 1983). Refinements to certain parameters led to reasonable results (Figure 6).

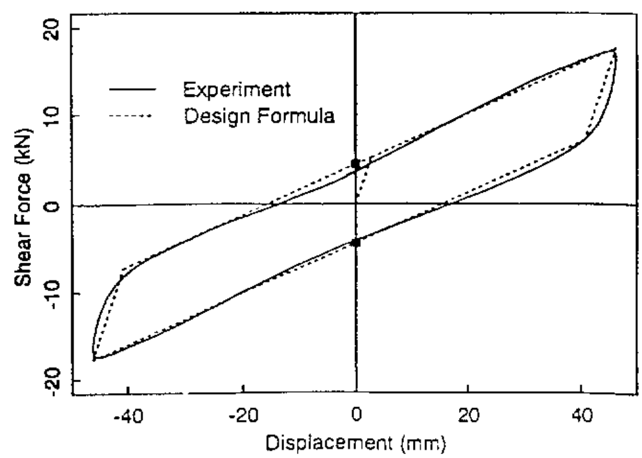


Fig. 6 Experimental and design formula hysteresis loops, lead-rubber bearing, 75 percent shear strain

20), nineteen 1.0 mm steel shims, and 12 mm top and bottom plates (Figure 1). The design axial pressure is 3.23 MPa. The bearings were designed with flange-type end plates to permit bolted structure and foundation connections. Fifteen bearings of this design were tested in this study.

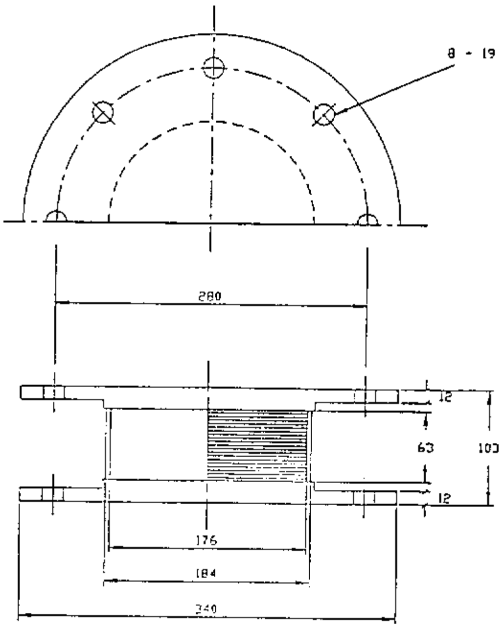


Fig. 1 Bearing design 1: high-damping A

2.2 *Design 2: High-damping B*

These bearings were made from a low-modulus, filled natural rubber compound, designated HDNR-S by the manufacturer, Rubber Consultants, Ltd., England. The shear modulus of this material varies from about 800 kPa at a shear strain of 5 percent to about 480 kPa at 50 percent strain and 400 kPa at 100 percent strain. The bearings consist of twelve layers of 4.0 mm thick rubber at 140 mm diameter (shape factor = 8.75), eleven 1.6 mm steel shims, and 20 mm top and bottom plates (Figure 2). The design axial pressure is 5.10 MPa. Bearing-structure and foundation connections are bolted. Instead of using flange-type end plates, the bearings are connected by bolting directly into the top and bottom end plates. Twelve bearings of this design were tested in this study.

2.3 *Design 3: Lead-rubber*

These bearings were made from an unfilled natural rubber compound, and contain a 25.4 mm diameter lead plug. For design purposes, the rubber shear modulus was assumed to have a constant value of 590 kPa. The bearings consist of 21 layers of 3.0 mm thick rubber at 180 mm diameter (shape factor = 15), twenty 1.0 mm steel shims, and 15 mm top and bottom plates (Figure 3). The design axial pressure is 3.08 MPa. These bearings have shear dowel end plate connections. The bearings were manufactured by Oiles Industries, Ltd., Japan. Fifteen bearings of this design were tested in this study.

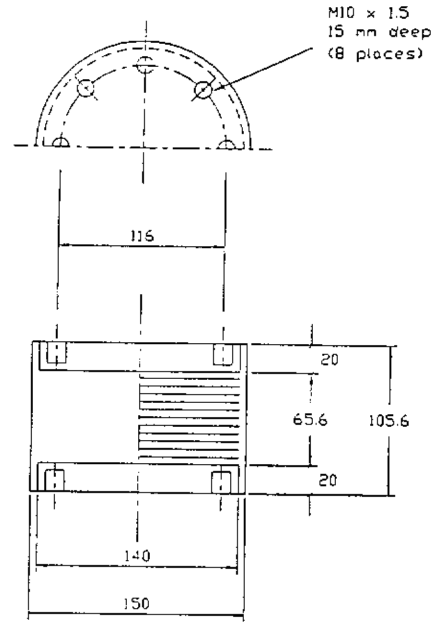


Fig. 2 Bearing design 2: high-damping B

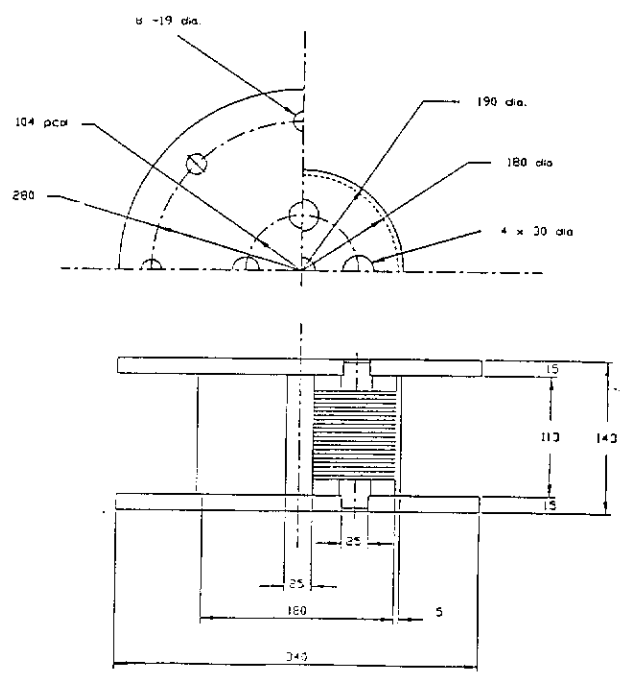


Fig. 3 Bearing design 3: lead-rubber

3 TYPES OF TESTS

All of the bearing tests were performed in a machine developed for general testing of small-to-moderate sized isolation bearings. The machine is capable of subjecting a bearing to simultaneous generalized horizontal and vertical dynamic loading. It has limits of 1335 kN vertical force, 534 kN horizontal force, and ± 250 mm horizontal displacement.

In addition to the horizontal shear tests, a large number of vertical tests were performed on the bearings. The results of these tests are not discussed in this paper.

3.1 *Characteristic tests*

1. Basic test

The basic type of test performed on all of the bearings of each design was a sinusoidal horizontal displacement-controlled loading, conducted at either 49.0 kN or 78.5 kN constant axial load and for 5 cycles of loading at shear strain amplitudes of 5, 25, 50, 75, and 100 percent. The axial loads selected correspond to the axial loads to which the bearings were subjected in the earthquake simulator tests of the 1/2.5-scale model of the full-size isolated building (Kelly, 1992). The frequency of loading was 1 Hz for all of these tests.

2. Variable axial load

The basic test was also performed at a number of different axial loads. The load was constant during each test, and tests were performed at loads of $3P_{des}$, $2P_{des}$, P_{des}, $P_{des}/2$, 0, and $-P_{des}/10$, where P_{des} was 49.0 kN or 78.5 kN. The rate of loading and the strain increments were otherwise the same as for the basic test described above.

3. Variable frequency

The basic test was also performed at loading frequencies of 0.1, 0.3, 0.5, 1.0, and 2.0 Hz. The other test variables were the same as those for the basic test.

3.2 *Ultimate tests*

1. Large-strain cyclic

Large-strain sinusoidal cycles at strain amplitudes of 100, 150, 200, 250, 300, and 350 percent were performed. (Maximum strain for the design 3 bearings was 200 percent, limited by the onset of roll-out instability; loading frequency was 0.5Hz for the 250, 300, and 350 percent tests).

2. Monotonic shear failure

Two bearings of designs 1 and 2 were failed in shear under monotonic loading. One bearing was tested under zero axial load, and the other at 78.5 kN axial load. The ultimate-level shear tests of the design 3 bearings consisted of determining the roll-out displacement of the bearings under different axial loads. Roll-out tests were performed at axial loads of 0, 49.0, 78.5, and 156.9 kN.

3. Monotonic tension failure

One bearing each of designs 1 and 2 was tested to break under monotonic tension loading. (The doweled connection detail of the design 3 bearings did not permit tension load to be applied to these bearings).

4 TEST RESULTS

Typical hysteresis loops for the three types of bearings under sinusoidal shear displacement loading are presented in Figure 4. The loops shown for the high-damping A bearing are at shear strains of 200, 250, 300, and 350 percent, those for the high-damping B bearing are at strains of 100, 150, 200, and 250 percent, and those for the lead-rubber bearing are at strains of 50, 100, 150, and 200 percent. Beyond a certain strain level, the high-damping bearings exhibit a clear stiffening behavior. Various results are presented and discussed in the following sections.

4.1 *Characteristic tests*

Bearing effective stiffness and damping were calculated from the experimental hysteresis loops using the following relationships:

$$k_{eff} = \frac{F_{max} - F_{min}}{d_{max} - d_{min}} \qquad (1)$$

$$\xi = \frac{W_d}{4\pi W_s} \qquad (2)$$

where:

F_{max}, F_{min} = peak values of shear force

d_{max}, d_{min} = peak values of shear displacement

W_d = hysteresis loop area

$W_s = \frac{1}{2} F_{max} d_{max}$

These properties are plotted as a function of shear strain for each type of bearing in Figure 5. The design 1 and 3 bearings show very similar effective stiffness-strain relationships. This is to be expected, as the original design intent for these two types of bearings was that their stiffness properties be the same. The design 2 bearings, however, show a much lower stiffness, about one-third of the stiffness of design 1 or 3 over the entire strain range. The damping ratios of the three bearing designs show greater differences. For design 1, the damping ratio decreases gradually from 12 percent at small strains to about 10 percent at strains above 200 percent. The design 2 bearings have an almost constant damping ratio of about 9-10 percent for strains up to 150 percent, which increases to about 14 percent at 250 percent strain. The design 3 bearings have the highest damping ratio: nearly 19

The influence of axial load variation on the shear stiffness of the design 1 and 2 bearings is shown in Figure 7. The curve for the design 3 bearings is very similar to that of the design 1 bearings, with neither design exhibiting any significant stiffness variation with axial load. Using k_{eff} at P = 78.5 kN as the reference stiffness, the stiffness variations at 25 and 100 percent strain for these bearings is only about ±5 percent of the 78.5 kN stiffness. The variation for the design 2 bearings is somewhat greater, being about ±20 percent of the 78.5 kN stiffness. Axial load variations influence damping ratios more than stiffness for all three bearing designs. The design 1 bearing damping ratio varies from 11 to 14 percent at 25 percent strain, and from 10 to 12 percent at 100 percent strain, and the design 3 bearing damping ratio varies from 15 to 21 percent at 25 percent strain, and from 13 to 16 percent at 100 percent strain. The design 2 bearing damping ratio varied more, from 8 to 14 percent at 25 percent strain, and from 6 to 15 percent at 100 percent strain.

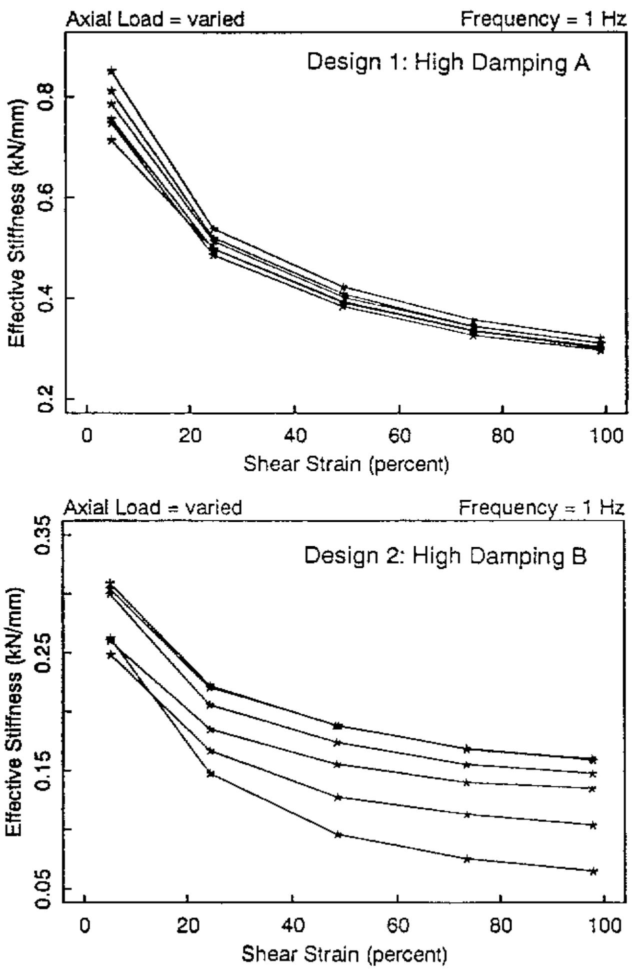


Fig. 7 Effect of axial load on effective stiffness, designs 1 and 2

Loading frequency effects on stiffness and damping ratio are shown in Figure 8 for the design 3 bearings. Stiffness is negligibly affected by the variation in loading frequency for all of the three designs. Using k_{eff} at 0.5 Hz as the reference stiffness, the lead-rubber bearing stiffness variation at 25 and 100 percent shear strain is only about ±2 percent of the 0.5 Hz stiffness. The variation for the high-damping bearings is about ±10 percent, and about ±6 percent of the 0.5 Hz stiffness for designs 1 and 2, respectively. Damping ratio is influenced less by load frequency than by axial load. The variation is about ±5 to 10 percent for all three bearing types, when compared to the damping ratio at 0.5 Hz.

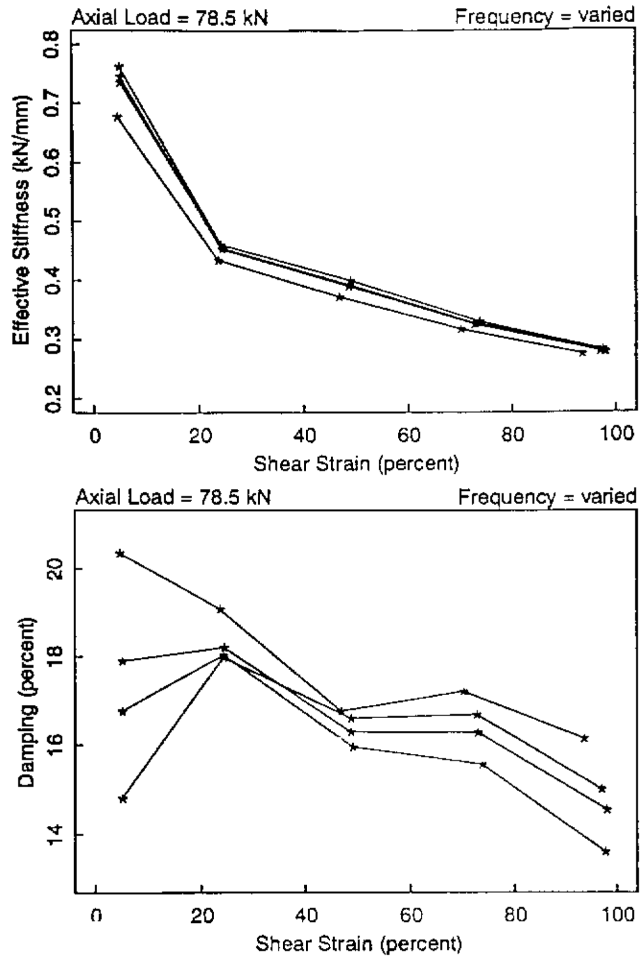


Fig. 8 Effect of loading frequency on bearing properties, design 3

4.2 *Ultimate tests*

1. Large-strain cyclic

Large-strain cyclic tests up to 350 percent shear strain were performed on the design 1 bearings, up to 250 percent on the design 2 bearings, and up to 200 percent on the design 3 bearing. Hysteresis loops for these tests are shown in Figure 4. Both types of high-damping bearings exhibit a stiffening characteristic at large strains. The high-damping A bearings begin to stiffen at about 250 percent and the high-damping B bearings at about 200 percent shear strain. High-strain stiffening is a material property of filled rubbers. The lead-rubber bearing, which is made from unfilled natural rubber and has doweled shear connections (which permit instability in the bearing before it can sustain extreme lateral displacements) does not show this stiffening effect at large strains.

2. Monotonic shear failure

Shear failure force-displacement curves for a design 1 and a design 2 bearing under zero axial load are shown in Figure 9. The design 1 bearing failed at a strain of 739 percent, and the design 2 bearing at about 510 percent. The peak shear forces at failure were 274 kN and 116 kN for the design 1 and 2 bearings, respectively. These forces correspond to shear stresses of 11.2 MPa for the design 1 bearing, and 7.5 MPa for the design 2 bearing. The failure mechanisms for both bearings involved tensile material rupture. Elastomer-shim bond separation was not observed in any of the bearing shear failures.

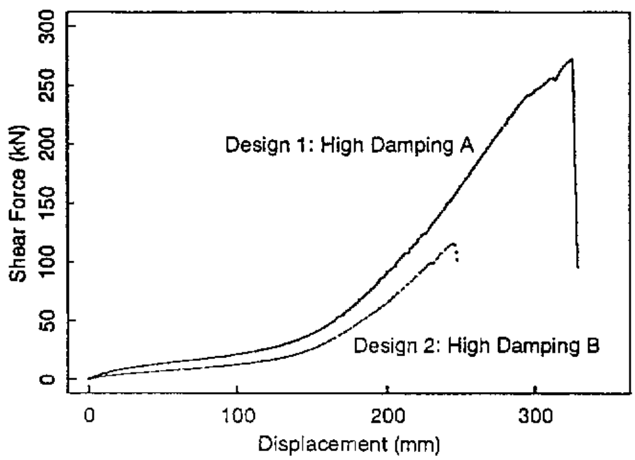


Fig. 9 Monotonic shear failure, designs 1 and 2

Roll-out strains ranged from 133 to 200 percent, reached in the 0 and 78.5 kN axial load tests, respectively. The calculated roll-out displacements for the 49.0 and 78.5 kN axial loads agree well with the experimental results, however, agreement is not so good for the 0 and 156.9 kN loads.

3. Monotonic tension failure

Tensile stress versus tensile strain curves for the failure tests of one design 1 and one design 2 bearing are plotted in Figure 10. The sharp reduction in stiffness in both curves at a stress of about 2 MPa indicates the onset of cavitation in the elastomer. The design 1 bearing reached a stress of 7.7 MPa and a strain of 514 percent at failure, while the design 2 bearing reached a stress of 8.0 MPa and a strain of 408 percent. These failure stresses represent a tension load of about two times the design compression load for the bearings. Future ultimate-level tests under combined large shear deformation and tension loading are planned. This type of test will more closely represent, than the pure tension tests described here, the type of extreme loading condition in which tensile stresses may develop in isolators.

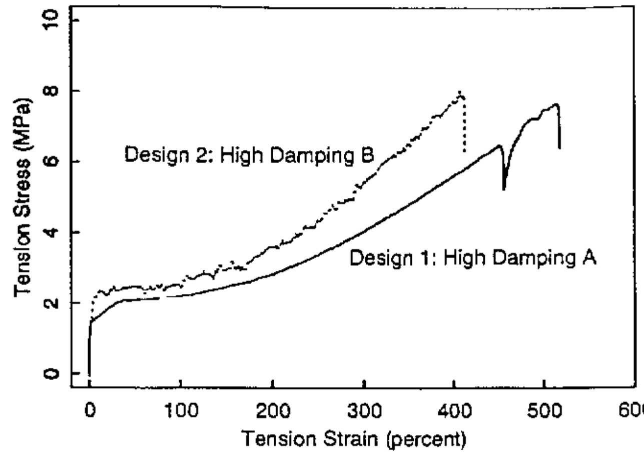


Fig. 10 Tension failure, designs 1 and 2

5 CONCLUSIONS

All of the bearings performed well in the large range of tests conducted. This experimental investigation has provided an extensive database for the confirmation and refinement of existing analytical models for isolation bearing properties.

Fundamental bearing characteristics of stiffness and damping were studied in terms of shear strain, axial load, and rate of loading. In general, it was found that variations in axial load and rate of loading did not significantly affect bearing stiffness and damping properties for moderate shear strain levels. The understanding of the failure mechanisms of seismic isolators has been enhanced by the various ultimate-level tests performed. The ultimate-level shear tests achieved bearing shear strains in excess of 500 percent before failure occurred. The tension failure tests revealed the very large tension capacity of the bolted high-damping bearings.

The results and conclusions will directly benefit the designers of isolation systems utilizing these types of bearings, providing a greater understanding of and confidence in bearing properties and behavior.

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