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CORRELATION OF ELASTOMER MATERIAL PROPERTIES FROM SMALL SPECIMEN TESTS AND SCALE-SIZE BEARING TESTS

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Abstract

Tests were performed on small-size elastomer specimens and scale-size laminated elastomeric bearings to correlate the material properties in shear between the two types of tests. An objective of the tests was to see how well the material properties that were determined from specimen tests could predict the response of scale-size laminated elastomeric bearings. Another objective was to compare the results of specimen test and scale-size bearing test conducted by different testing organizations. A comparison between the test results from different organizations on small specimens showed very good agreement. In contrast, the correlation of scale-size bearing tests showed differences in bearing stiffness.

Introduction

Over the past several years, the Engineering Mechanics Program of the Reactor Engineering Division of Argonne National Laboratory (ANL) has been actively involved in research and development efforts related to the use of laminated elastomeric bearings for seismic isolation. The use of these isolators has been increasing rapidly worldwide. This R&D effort encompassed the following areas: testing elastomer specimens (Kulak and Hughes, 1991) (Kulak and Hughes, 1992), designing bearings, developing bearing technical specifications for procurement (Kulak, 1992), testing scale-size bearings (Kelly, 1991), in-situ bearing testing under a full-size building (Seidensticker, 1989) and computer code development (Kulak and Wang, 1991) (Kulak, Wang, and Hughes, 1991). An Elastomer Testing Facility has been established at Argonne to perform high precision dynamic testing of small elastomer test specimens.

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The purposes of this paper are (1) to compare the material properties determined from specimen tests with those back calculated from scale-size bearing tests and (2) to compare test results from several organizations. This report is based on test results of two different elastomers compounded by LTV Energy Products Company (Oil States Industries Division) of Arlington, Texas. The first compound was identified by them as 259-62 and the second as 257-71. Extensive testing of small specimens is part of the experimental work being performed at Argonne. A limited amount of testing of small specimens is required by the bearing manufacturer for each lot of elastomer used in a bearing. Results from these two sources were used to create a specimen-test database.

ANL designed four types of elastomeric seismic isolation bearings for testing at the Earthquake Engineering Research Center (EERC) of the University of California at Berkeley. One-half of the 28 bearings were molded from compound 259-62 and the other half from the 257-71 compound. LTV was required to perform limited tests (i.e., acceptance tests) on each bearing according to ANL's procurement technical specifications. Results from the EERC test program and the LTV acceptance tests were used to form the scale-size-bearing database.

Small Specimen Tests

In this paper, the term specimen refers to a piece of elastomer that is specially prepared (shaped) for testing. A small quantity of compound is obtained after the natural rubber and additives are mixed in a Banbury mixer and calendered into sheets. The small quantity of compound is extruded into a multi-cavity mold containing steel bars to make two sibling specimens. The assembly is heated to vulcanize the rubber to an equivalent cure as that of the bearing. The unused calendered rubber sheets may be calendered again and then placed with alternate layers of steel plates (shims) into a compression mold. The mold is then placed into a four-post molding press and subjected to heat and pressure to vulcanize the rubber and produce an isolation bearing. The important point to note here is that the test specimens are not taken as samples of elastomer from a molded bearing, but the specimens are samples taken from a batch of rubber that subsequently was used in a bearing. The specimens for these tests are made up of two rubber pads (approx. 1 in. in area and 0.2 in. thick) bonded to three steel pieces as shown in Figure 1. The tests are conducted by holding the outer bars steady and pulling and pushing on the center bar for the required shear motion.

Two quantities that characterize the behavior of an isolator are the shear stiffness and damping. The shear stiffness of the isolator is a quantity that governs the fundamental horizontal frequency of a base isolated system. Because of the relatively high shear modulus of the steel, it is the shear modulus of the elastomer that determines the shear stiffness of the bearing. Damping is another quantity use to characterize the elastomer. Here the effective shear modulus, G_{eff}, and an effective damping ratio, β, are defined by

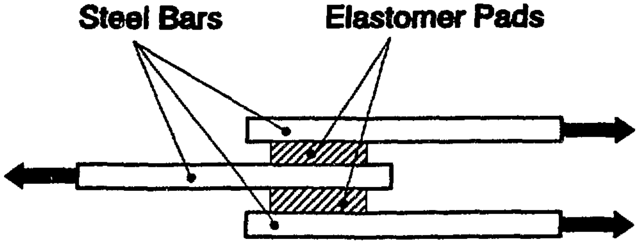

Figure 1. Three-Bar-Lap Shear Specimen

$$G_{eff} = \frac{\tau^{+}_{max} - \tau^{-}_{max}}{\gamma^{+}_{max} - \gamma^{-}_{max}}, \qquad \beta = \frac{W_D}{2\pi W_S} \tag{1}$$

where τ^{+}_{max} and τ^{-}_{max} are the maximum positive and negative shear stresses, respectively, γ and γ are the maximum positive and negative shear strains, respectively, W_S is the energy stored during a cycle and W_D is the energy dissipated during the cycle.

Testing Facilities

The tests conducted at ANL were performed on one of Instron Corporation's new generation of 8500 series universal testing instruments, which use a computer-based system to provide full digital control of the machine. Our machine is a model 8502 servo-hydraulic unit that was configured especially for low frequency elastomer testing.

LTV performs small specimen testing of the bearing elastomer as part of their quality control procedure. Shear modulus tests are carried out in a laboratory environment. The tests are performed on an MTS servo-hydraulic universal testing machine with analog electronics that uses a PC for control, data acquisition and data interpretation. Hysteresis loops are plotted on a pen plotter. This machine is approximately comparable to the Instron.

Test Results

Dynamic property tests were performed at LTV and ANL on elastomer specimens. The tests were performed at shear strain levels of 50% and 100% and at frequencies of 0.005 Hz and 0.5 Hz, which are, respectively, the nominal acceptance test frequency and the nominal design frequency. Typical hysteresis loops, obtained by ANL, for the 100% strain level are shown in Figure 2 for the 259 compound. Table 1 summarizes the results for compound 259-62 and compound 257-71. The ratio of energy dissipated at 100% shear strain to that at 50% shear strain ranges from 2.6 to 2.9. A pure viscous dissipation would have a value of 4.0 and a pure hysteretic dissipation would have a value of 2.

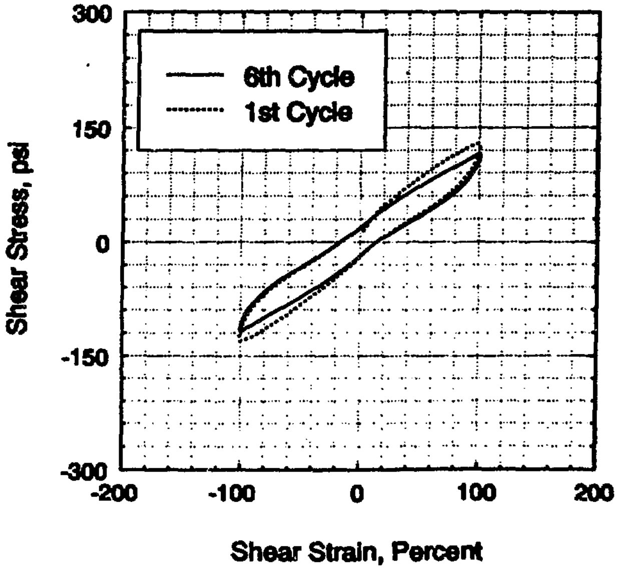

Figure 2. Hysteresis loops for compound 259-62 at 100% strain

Table 1. Comparison of results from specimen tests.

Tester	Compound 259-62				Compound 257-71			
	50% Strain		100% Strain		50% Strain		100% Strain	
	G_{eff} (psi)	W_d (in-lb/in_3)	G_{eff} (psi)	W_d (in-lb/in_3)	G_{eff} (psi)	W_d (in-lb/in_3)	G_{eff} (psi)	W_d (in-lb/in_3)
LTV	154	28	115	74	208	39	149	103
LTV	159	28	125	73	214	40	165	114
LTV	147	29	115	80	211	39	154	98
ANL	146	25	115	80	187	38	155	111
Mean	152	28	118	75	205	39	156	107

Scale-Size Bearings

ANL designed four types of elastomeric seismic isolation bearings that were acceptance tested at LTV and dynamically tested at EERC. The four different types of isolators were made from two different rubber compounds (259-62 and 257-71), designed to two different shape factors (9 and 18), and had two different diameters (14 in. and 16 in.). The following four bearing types were identified: Type 1 (compound 259, shape factor of 9, outside diameter of 16 in.), Type 2 (compound 259, shape factor of 18, outside diameter of 16 in.), Type 3 (compound 257, shape factor of 9, outside diameter of 14 in.) and Type 4 (compound 257, shape factor of 18, outside diameter of 14 in.). A typical Type 1 bearing is shown in Figure 3. These isolators were designed to provide a horizontal frequency of 0.5 Hz at 100% shear strain. These bearings were acceptance tested in pairs at the manufacture's facility. A molding press was retrofitted with a hydraulic cylinder to do combined compression-shear testing of the isolators. Subsequently, the twenty-eight scale-size bearings, seven of each type, were dynamically tested at EERC. The mechanical characteristic tests for the elastomeric bearings were performed in a test machine capable of subjecting single bearings to simultaneous generalized horizontal and vertical dynamic loadings. This machine was specifically designed to test single bearings.

The shear stiffness of the isolator is one quantity that determines the fundamental horizontal frequency of a base isolated system. For design purposes, the bearing stiffness is usually computed by

$$K_{eff} = \frac{G_{eff}\, A_r}{t_r} \tag{2}$$

where G_{eff} is the effective shear modulus at the design strain, A_r is the plan area of the rubber excluding the cover rubber and t_r is the total thickness of the rubber between the end plates.

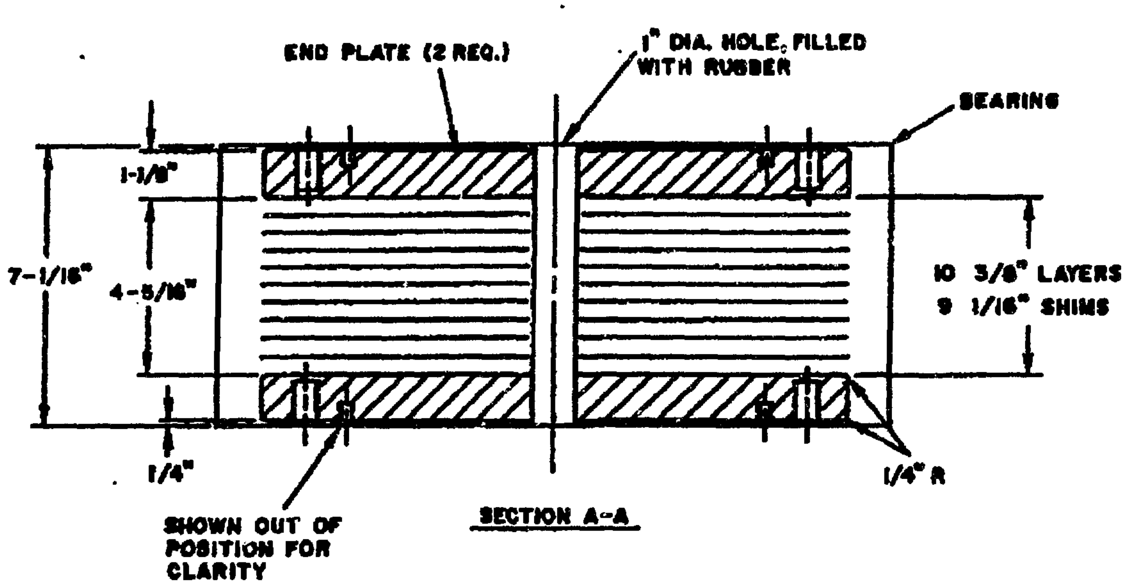

Figure 3. Steel laminated elastomeric seismic isolation bearing.

Calculation of Material Properties

An effective stiffness, K_{eff}, which is determined from the hysteresis loops, is used to characterize the bearing at each strain level. Experimental results from this study had both symmetric and asymmetric hysteresis loops. The effective stiffness for symmetric and asymmetric loops is calculated, respectively, by

$$K_{eff} = \frac{F^{+}_{max} - F^{-}_{max}}{u^{+}_{max} - u^{-}_{max}}, \quad K^{+}_{eff} = \frac{F^{+}_{max}}{u^{+}_{max}}, \quad K^{-}_{eff} = \frac{F^{-}_{max}}{u^{-}_{max}} \tag{3}$$

where F^{+}_{max}, F^{-}_{max}, u^{+}_{max} and u^{-}_{max} are the maximum positive and negative forces and displacements, respectively. Thus, it is seen that K_{eff} defines a stiffness for a symmetric loop; K^{+}_{eff} defines a positive-side stiffness and K^{-}_{eff} defines a negative side stiffness. The shear modulus, G_{eff}, is then back calculated from Equation 2. The damping ratio, β, for the bearing is calculated from Equation 1. However, the energy stored during a cycle, W_S, and the energy dissipated during the cycle, W_D, pertain to the entire bearing.

Test Results

EERC performed dynamic horizontal shear tests at 50% and 100% shear strain on six bearings of Type 1, three Type 2 bearings, five of Type 3 and six of Type 4. Figure 4 shows a typical hysteresis loop from a bearing test. The test results for the Type 1 design are tabulated in Table 2.

Combined compression and shear tests were performed by LTV as part of the acceptance tests for each isolator. The bearings were loaded vertically to 65 tons (i.e., 845 psi for Type 1 and 2 bearings and 1150 psi for Type 3 and Type 4 bearings) and displaced to 3.75 in. (i.e., 100% shear strain). Figures 5 and 6 show typical symmetric and asymmetric hysteresis loops, respectively. The remaining three bearings were not tested because of time constraints. Only nine of the twenty-four bearings exhibited symmetric behavior as indicated by their force displacement signatures.

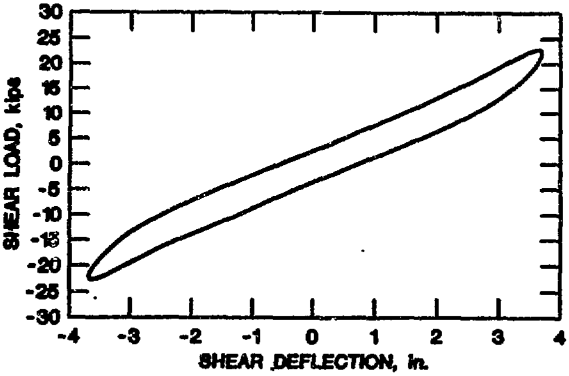

Figure 4 Typical hysteresis loop obtained during dynamic bearing tests

Table 2. Dynamic test results for bearing type 1 at 0.5 Hz

Bearing SN	50% Shear Strain K_{eff} (kips/in.)	G (psi)	β (%)	100% Shear Strain K_{eff} (kips/in.)	G (psi)	β (%)	Pressure (psi)
1	7.2	175	10.61	6.2	151	8.64	819
2	6.54	159	10.32	5.6	136	8.78	819
3	5.6	137	10.19	4.8	118	8.64	819
5	5.3	129	10.22	4.3	105	9.25	819
6	6.2	150	9.34	5.3	130	8.19	806
7	6.5	159	10.70	5.3	128	8.61	812

Table 3 shows the results for the six Type 1 (compound 259-62) bearings tested. Only two of the six bearings exhibited symmetric response. For both bearings the effective stiffness was 4.8 kips/in. and the back calculated effective shear modulus was 117 psi. The specimen test results for this compound (Table 1) had an average value of 118 psi at a testing frequency of 0.5 Hz. However, the acceptance test was performed at a frequency near 0.005 Hz. The remaining four asymmetric responding bearings had a positive-side stiffness ranging from 4.7 to 5.2 kips/in. and a negative-side stiffness from 49 to 51 kips/in. The resulting stiffness, G_{eff}^{+}, was from 114 psi to 127 psi and G_{eff}^{-} was from 49 psi to 51 psi.

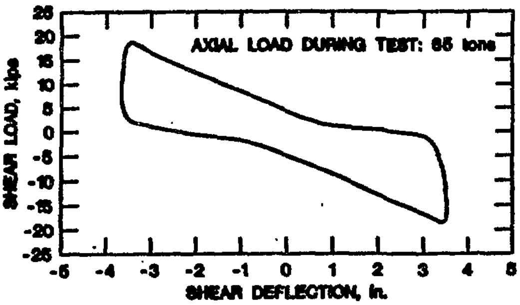

Figure 5. Symmetric hysteresis loop obtained during acceptance testing.

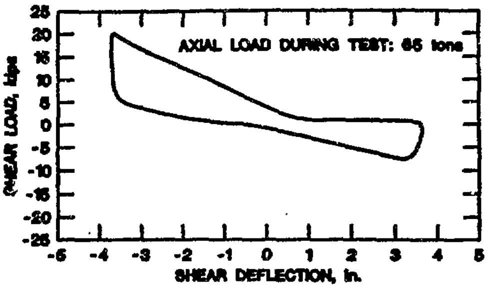

Figure 6. Asymmetric hysteresis loop obtained during acceptance testing.

Table 3. Acceptance test results bearing type 1 at 0.005 Hz.

SN	K_{eff} (kips/in.)	K^{+}_{eff} (kips/in.)	K^{-}_{eff} (kips/in.)	G_{eff} (psi)	G^{+}_{eff} (psi)	G^{-}_{eff} (psi)
1	NA	5.2	2.0	NA	127	49
2	4.8	NA	NA	117	NA	NA
3	NA	5.2	2.0	NA	127	49
4	4.8	NA	NA	117	NA	NA
5	NA	4.7	2.0	NA	114	49
6	NA	4.7	2.1	NA	114	51

NA = not applicable

Correlation of Results

Tests were performed by ANL and LTV on small specimens of elastomers used for seismic isolators. Scale-size bearings were tested by EERC and LTV. This section compares the results between the following: (1) specimen tests, (2) bearing tests and (3) specimen test and scale-size bearing tests.

Specimen Tests Correlation

The results of specimen testing were described above. A comparison of results for both compounds is presented in Table 1 for the 50% and 100% strain levels. For compound 259-62 at the 50% strain level, the ANL test result was within 5% of the average value obtained by the manufacturer. At the 100% shear strain level, the ANL result was within 3% of LTV's average value. For compound 257-71, the ANL results were within 12% and 1%, respectively, of the manufacturer's results at the 50% and 100% strain levels.

Scale-size Bearing Tests Correlation

The results of dynamic tests on four different types of elastomeric seismic isolation bearings described above are compared here with the acceptance test results for these bearings. A notable difference in bearing response between the two types of tests is the difference in the shape of the hysteresis loops. All the loops obtained during dynamic testing are of a near elliptical shape with symmetry about both axes. The near elliptical shape also was obtained during all the specimen tests. The shape of the hysteresis loops obtained during the acceptance tests, however, resemble a "bow" tie, which is not characteristic of the response of elastomeric materials. In addition, only nine (9) of the 24 bearings tested had symmetric loops, that is a mirror image response in opposite directions. The 15 bearings with the abnormal hysteresis loops had different effective stiffness in the positive and negative directions. Because of this difference in bearing response, we felt that the tests that produced asymmetric loops should be excluded from the correlation.

A comparison of bearing stiffness among all four bearing types showed that the dynamic results were from 12% to 32% higher than the acceptance test results. A part of this difference could be due to testing frequency effects. Recall, the acceptance tests were performed at 0.005 Hz, while the dynamic tests were conducted at 0.5 Hz. Another reason for this difference was that the dynamic tests were performed in a laboratory with specialized test equipment while the acceptance test was performed in the molding plant with an *ad hoc* testing arrangement.

Specimen Tests and Scale-size Dynamic Bearing Test Correlations

The comparison between specimen tests and dynamic bearing tests are discussed in this section. We have included both the ANL and LTV tests as part of the specimen database for both compounds. Bearing Types 1 and 2 are included in the compound 259-62 bearing database and bearing Types 3 and 4 are included in the compound 257-71 bearing database.

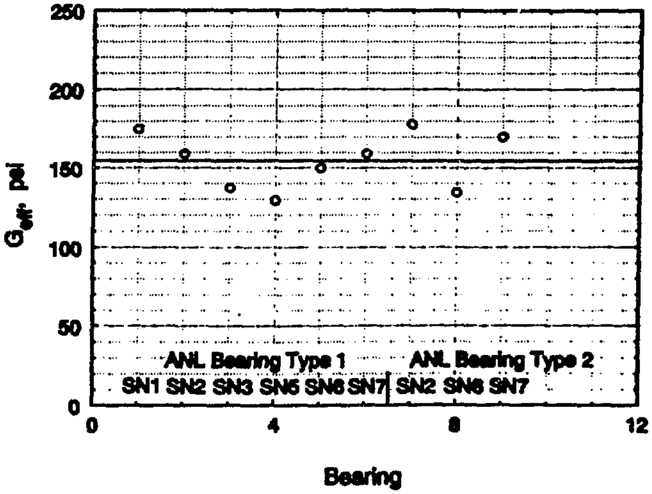

Figure 7. Effective shear modulus at 50% shear strain for bearings molded from compound 259-62.

Figure 7 shows the back-calculated effective shear modulus for all bearings made from compound 259-62, which includes bearings classified as Type 1 and

Table 4. Comparison of back-calculated shear modulus for scale-size bearings.

Shear Strain (%)	Effective Shear Modulus			
	Compound 259		Compound 271	
	Mean (psi)	c.o.v. (%)	Mean (psi)	c.o.v. (%)
50	155	11.8	212	5.4
100	131	12.7	187	5.3

Table 5. Comparison of the mean shear modulus from specimen and bearing tests.

Shear Strain	Compound 259-62			Compound 257-71		
	Specimen	Bearing	Difference (%)	Specimen	Bearing	Difference (%)
50%	152 psi	155 psi	2.0	205 psi	212 psi	3.4
100%	118 psi	131 psi	11.0	156 psi	187 psi	19.9

Type 2. Table 4 compares the back-calculated shear modulus from the scale-size bearing tests for each compound. It is seen that the highest coefficient-of-variation (c.o.v.) was 12.7% for compound 259-62 at the 100% strain level. This is an acceptable value for this type of product. Table 5 presents a comparison between the shear modulus as determined from specimen testing and dynamic scale-size bearing testing. The mean value for the shear modulus from the bearing database for both compounds at 50% shear strain is within 4% of the value from the specimen database. For compound 259-62 at the 100% strain level, the mean shear modulus from the bearing database is 11% higher than the value from the specimen database. For compound 257-71, the bearing database value was 20% higher than the specimen database value.

Conclusions

The results of small specimen testing performed at ANL and at LTV showed very good agreement. All results for the effective modulus at the 50% and 100% strain levels were within 10% for both rubber compounds. Agreement was as good as 1% for the test of LTV compound 257-71 at the 100% shear strain level. This high correlation is probably because the testing was conducted under controlled laboratory conditions with high quality testing machines by both organizations. A significant variation in elastomer stiffness was found for both compounds over the frequency range of 0.005 to 0.5 Hz, which spans the acceptance-test frequency and the nominal design frequency.

A comparison of results from scale-size bearing tests performed by the manufacture and an independent testing organization revealed some differences. The manufacture's tests always gave bearing stiffnesses that were less than those obtained by the testing organization. This difference could be due to the difference in test frequency employed by each organization. The frequency dependency was noted during specimen testing. Another difference was the shape of the hysteresis loops produced during testing, and this difference is attributed to the use of significantly different testing machines by the organizations.

A correlation between the specimen tests results and the bearing tests results was made. At the higher strain level, significant differences between results from specimen tests and bearing test were found. These could be attributed to geometric effects that are not present at the lower strain levels. The geometric effects are not accounted for in the simple formulas used, and may indicate a need to perform finite element analysis to better predict the stiffness at the higher strain levels.

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