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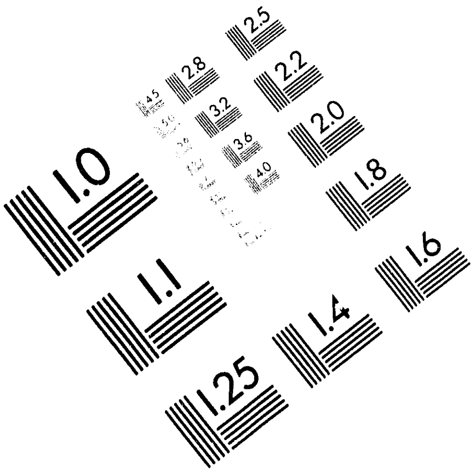

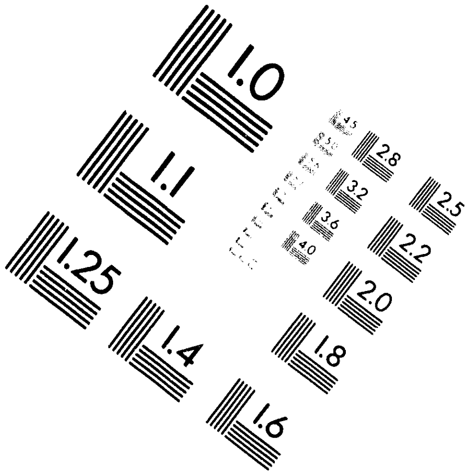

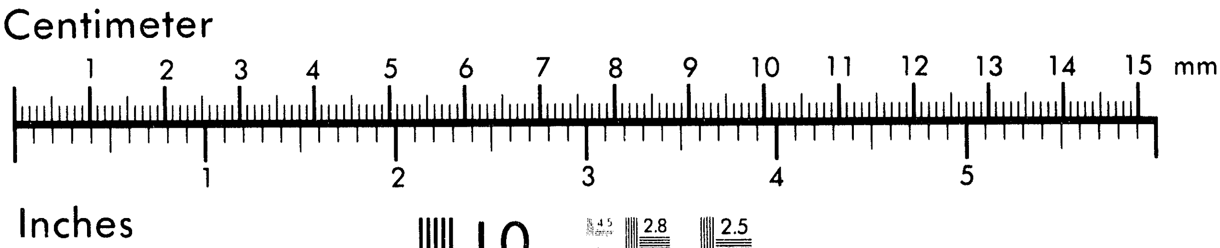

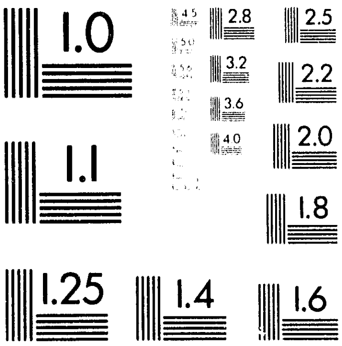

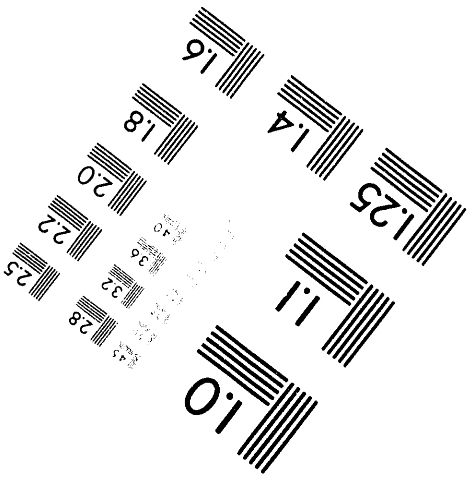

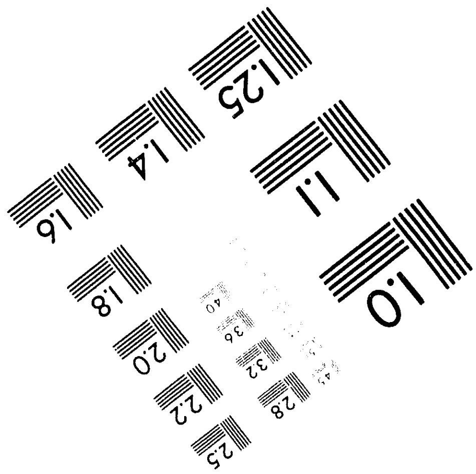

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CONF-940613--17 ANL/RE/CP--82468

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IDENTIFICATION OF FACTORS THAT INFLUENCE THE STIFFNESS OF HIGH-DAMPING ELASTOMER SEISMIC ISOLATION BEARINGS

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ABSTRACT

During the past decade, high-damping elastomer, steel-laminated seismic isolation bearings have gained acceptance as a device for isolating large buildings and structures from earthquake damage. In the United States, architectural engineering firms custom design isolators for each project and then have the isolators manufactured by one of less than a hand-full of manufactures. The stiffness of the bearing is the single most important design parameter that the molded bearing must meet because it determines the fundamental frequency of the isolation system.

This paper reports on recent research that examined several factors that cause real and potential variations to the stiffness of the bearing. The resulting changes to the fundamental frequency of the isolated structure are quantified for each factor. The following were examined: (1) dimensional tolerances, (2) frequency effects, (3) temperature effects, (4) cyclical effects, and (5) aging effects. It was found that geometric variations barely affect the stiffness whereas temperature variations greatly affect the stiffness.

INTRODUCTION

During the past decade civil engineers have begun to accept base isolation as a viable strategy for protecting buildings and structures from the consequences of damaging earthquakes. This is evident by the inclusion of regulations for seismically-isolated structures in local building codes like California's SEAOC "Blue Book" (1990) and national codes like the Uniform Building Code (1991). Also, worldwide base isolation has been applied to medical centers, emergency control facilities, computer centers, nuclear power plants, bridges, museum pieces, etc. Isolated structures can be found in the following countries: Australia, Chile, China, the Former Soviet Union, France, Italy, Japan, Korea, New Zealand, South Africa, and the United States.

Several strategies have been employed to preclude structural failure from earthquakes. For example, with seismic hardening the structure is made "strong" to withstand the ground shaking; however, content damage and loss of life can still occur. Another approach is seismic base isolation. The main idea of base isolation is to decouple the structure from damaging ground motions by lowering the fundamental frequency of the structure so that it is below the energy containing frequency range of the earthquake. Seismic base isolation can eliminate damage to the structure, eliminate damage to the contents, and save lives. This was clearly shown during the recent earthquake that occurred in the Northridge section of the San Fernando Valley in southern California. The epicenter was about 20 miles northwest of Los Angeles, and the earthquake measured 6.6 on the Richter scale. Damages from this earthquake have been estimated to be near $30 billion with over 2000 hospital beds lost.

It has been reported (Civil Engineering, 1994) that the rebuilt Olive View Hospital in Sylmar, which collapsed during the 1971 earthquake that measured 6.4 on the Richter scale, used the seismic hardening design strategy and survived the Northridge quake without any structural damage. The hospital was subjected to 0.91 g horizontal ground acceleration that was amplified to 2.31 g at roof level and 0.60 g vertical ground acceleration. However, the contents were destroyed and the hospital had to be closed. In contrast, the base-isolated USC University Hospital recorded horizontal ground accelerations of 0.5 g at its base and 0.2 g just above the isolators. The base isolation system prevented structural damage, content damage, loss-of-life, and allowed the hospital to be fully operational during and after the quake.

This paper examines factors from elastomer testing, manufacturing procedures, and acceptance testing that could affect the performance of high-damping isolation bearings. The

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first part of this paper describes high-damping steel-laminated elastomeric bearings, the manufacturing process, and acceptance testing. The following sections identify several factors that can influence the stiffness of the bearing and, thus, change the system frequency from its design value. This is followed by quantifying the effect of variations in these factors on the system frequency. The last section presents the conclusions of this investigation.

LAMINATED ELASTOMER BEARINGS

There are several types of laminated isolation bearings available for mitigating the effects of earthquakes: natural rubber bearings, lead-core rubber bearings, and high-damping rubber bearings. To achieve viable seismic isolation, the system must provide stiffness and energy dissipation. Thus, a system that uses natural rubber bearings must include an additional damping device. The lead core provides energy dissipation for the lead-core rubber bearings, and specially compounded rubber provides damping for the high-damping rubber bearings. The work presented here only deals with high-damping rubber bearings.

The high-damping, steel-laminated, elastomeric bearing (Fig. 1) is becoming a preferred devices for isolating large buildings/structures up to eight stories. The current reference design for the Advance Liquid Metal Reactor (ALMR) uses these bearings for seismic isolation. These bearings are constructed from alternating layers of high-damping rubber and steel plates (shims). The elastomer is bonded to the plates during the vulcanization process. The rubber allows for large horizontal displacements, and the steel keeps the rubber from bulging outward from the vertical load and, thus, provides high vertical stiffness. There are thick steel end plates at the top and bottom of the bearing for mounting to the lower basemat and superstructure. It is common to include a circumferential layer of cover rubber beyond the steel plate diameter for protective purposes.

The bearings are typically designed for shear strains between

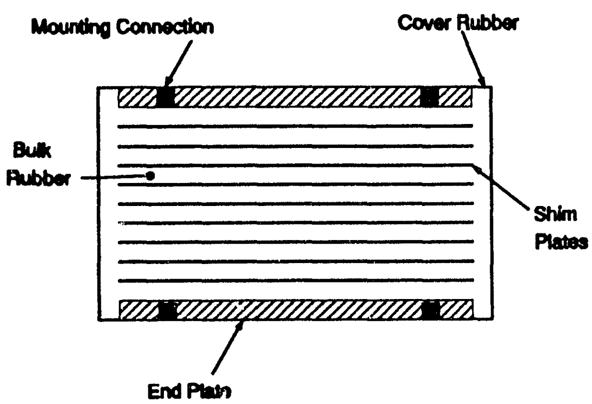

FIGURE 1. HIGH DAMPING STEEL-LAMINATED ISOLATION BEARING

50% and 100% and are expected to sustain two to three times these levels for beyond design basis loading conditions. Elastomeric bearings are currently designed to provide a system frequency between 0.4 and 0.8 Hz. Isolation bearings are expected to perform in the temperature range from -20 to 40°C (-4 to 104°F).

Currently, in the United States there are only two suppliers for this type of bearing: FURON of Athens, Texas and Oil States Industries of Arlington, Texas. In the United States, architectural engineering firms custom design isolators for each project and then have the isolators manufactured. For high-damping elastomeric bearings, off-the-shelf bearings are not currently available and, thus, must be custom designed and manufactured.

The fundamental horizontal frequency, f_H, of a seismic isolation system is given by

$$f_H = \frac{1}{2\pi}\sqrt{\frac{K_H}{M}} \qquad (1)$$

where K_H is the horizontal stiffness of all the isolators and M is the total mass supported by the isolators. The horizontal stiffness of a single bearing, k_H, is given by

$$k_H = \frac{GA}{t_r} \qquad (2)$$

where G is the shear stiffness of the elastomer, A is the planar cross-section area of the rubber, and t_r is the total thickness of the rubber between the end plates.

ANL TESTING FACILITY

Some work presented in this paper draws upon tests performed at Argonne National Laboratory (ANL), and this section gives a brief overview of the facility. The Elastomer Testing Facility at ANL is set up for high precision dynamic testing of small coupon specimens. The tests are performed on one of Instron Corporation's new generation of 8500 series universal testing machines which use a computer-based system to provide full digital control of the machine. The servohydraulic machine has a 5 kip actuator and sufficient hydraulic supply to test at frequencies up to 100 Hz. The machine is connected to a 386DX computer that has been programmed for test control, data acquisition and data processing. A small environmental chamber, only large enough to contain the specimen and its holder, is mounted on the testing machine to carry out the testing at temperatures that can range from -70°C to 200°C. The chamber is heated by electrical resistance heaters and cooled using the vaporization of liquid CO_2. Frequencies up to 100 Hz can be handled at very low strain levels. Two sample points on the system performance limiting curve would be 5 mm cyclic amplitude at 10 Hz and 40 mm at 1 Hz.

To obtain data appropriate to earthquake type events, small

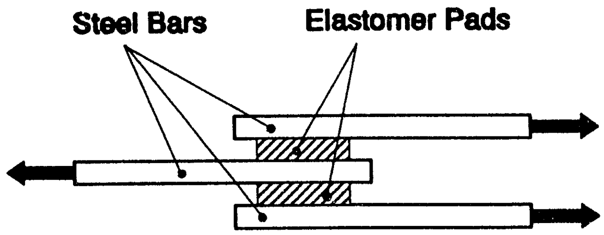

FIGURE 2. THREE-BAR SHEAR SPECIMEN

samples of the elastomer are subject to fully-reversed cyclical shear loading. The test specimens consist of two elastomer pads 5 mm thick by 25 mm square mounted in the three-bar lap configuration (Fig. 2). The specimens are fabricated in a mold by bonding the elastomer to the steel bars during vulcanization. The fixtures that hold the three-bar specimens will allow cyclic shear strain deformation up to 375% strain. ANL currently uses this design for all its elastomer testing and requires this type of specimen in the specifications for procurement of full-sized isolators.

FACTORS THAT INFLUENCE STIFFNESS

This section examines several factors that cause real and potential variations to the stiffness of the bearing from the design value.

Dimensional Tolerances

All manufactured parts are made within the limits of the specified dimensional tolerances. For laminated bearings, Eq. (2) shows that a bearing whose area is at the upper dimensional limit and rubber thickness is at the lower limit would produce the stiffest bearing, and the softest bearing is manufactured when the area is the smallest and the rubber thickness is the largest. Argonne has developed procurement specifications (Kulak, 1991) that were used to buy bearings for several research projects. Applying the tolerances in these specifications to six different designs that were purchased for several projects, it was found that the largest variations in stiffness were 6.5% above the design value and 6.1% below the design value.

Frequency Effects

The design frequency for seismic isolation systems falls between 0.4 to 0.8 Hz, which is usually below the high energy content range of most earthquakes. It is generally accepted that the response of isolation systems is independent of frequency for the frequencies normally associated with earthquakes. The research at Argonne generally supports this fact with one exception. The testing of full-size bearings requires highly specialized bearing testing machines that can load the isolators to and beyond the design range at the design frequency. U.S. bearing manufacturers currently have machines that can test isolators well beyond the design displacement, but they cannot test them at the design frequency of say 0.5 Hz. Acceptance tests are usually performed at approximately 0.002 to 0.005 Hz, which is two decades below the design frequency. Thus, if a bearing meets the design stiffness at 0.002 Hz it may not satisfy the requirements at 0.5 Hz. Recent small-size specimen testing (Kulak and Hughes, 1993) show that there could be about a 15% increase in stiffness between tests run at 0.002 Hz and those run at 0.5 Hz. Current purchase specifications allow a ±10% variation. For example, a bearing that is 10% above the nominal design value at 0.002 Hz could be as much as 27% above at 0.5 Hz. Therefore, when an extremely low acceptance testing frequency is used, misleading values for the bearing stiffness at the design frequency may be obtained. New elastomer compounds are being developed to improve performance and increase damping. It is possible that some of these new compounds may be more sensitive to frequency effects and therefore should be extensively tested.

Temperature Effects

Within the continental United States, seismic isolation bearings in service could be exposed to environmental temperatures ranging from -20 to 40°C (-4 to 104°F). Therefore, the influence of temperature on the performance characteristics of elastomeric bearings could be significant. Tests to find the variation of material properties (i.e., shear stiffness and energy dissipation) were reported by Kulak and Hughes (1993).

All tests were performed at 0.5 Hz and at both 50% and 100% strain. Because of the expense of cooling the environmental chamber a group of tests at a particular shear strain level was conducted in about five hours over the entire temperature range. The specimen was held only for about two minutes at the required temperature and the test performed. Since there was concern about the effect of these short hold times, another test sequence was run for three hours with the specimen held at -20°C and no variation in the test results was observed. The results are presented in Figs. 3 and 4. The effective modulus values show a significant increase as the temperature is reduced. The unconnected data points (triangles) for the 100% tests illustrate the effect of temperature on recovery. The tests denoted by triangles had short rest times and at temperatures below room temperature yielded lower values of effective modulus. The material recovers rapidly at temperatures above 30°C yielding identical values of modulus. The effective damping ratio shows a significant increase with lower temperatures and this is very evident in the shape of the hysteresis loops. Figure 5 shows typical hysteresis loops at 100% shear strain for the design temperature and the coldest temperature of the design range.

Cyclical Effects

It is known that the stiffness of elastomers decreases with each additional cycle. The decrease is largest from the first to second cycle. Current testing procedures for elastomer small-specimen testing and bearing testing require that the shear modulus/ stiffness be recorded on the nth cycle. Typically, the nth cycle is the fifth or sixth cycle. A query to the manufacturer into the

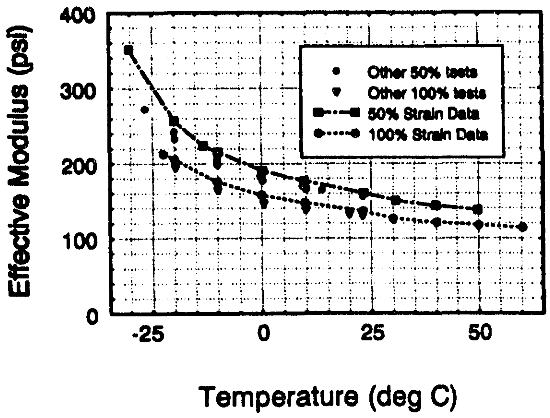

FIGURE 3. VARIATION OF EFFECTIVE MODULUS WITH TEMPERATURE

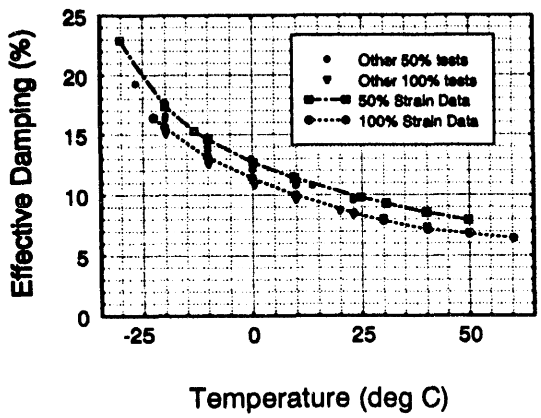

FIGURE 4. VARIATION OF DAMPING WITH TEMPERATURE

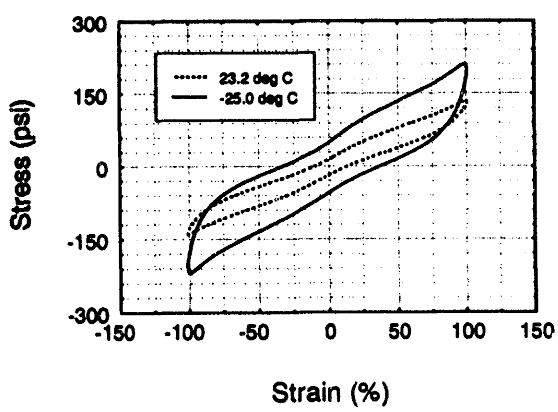

FIGURE 5. HYSTERESIS LOOPS FOR 100% SHEAR STRAIN

TABLE 1. CYCLICAL EFFECT ON SHEAR MODULUS

Shear Strain (%)	Shear Modulus, G (psi) G_1 (1st Cycle)	G_6 (6th Cycle)	Ratio G_1/G_6
50	155	143	1.08
100	126	114	1.11
150	137	116	1.18

TABLE 2. CYCLICAL-TEMPERATURE EFFECT ON SHEAR MODULUS (50% SHEAR STRAIN)

Temperature (°C)	(°F)	Shear Modulus, G (psi) G_1 (1st Cycle)	G_6 (6th Cycle)	Ratio G_1/G_6
40	104	152	143	1.06
23	73	175	161	1.09
10	50	193	177	1.09
0	32	209	191	1.09
-10	14	243	216	1.13
-20	-4	303	256	1.18

reason for this revealed that for quality control purposes more consistent results were obtained at the fifth and sixth cycle. However, during an earthquake the system could respond with a "first" cycle stiffness. Table 1 shows typical ratios of first-cycle stiffness to sixth-cycle stiffness that were obtained from small-specimen testing at Argonne's Elastomer Testing Facility. The test was conducted at room temperature and at the shear strain levels of 50, 100, and 150%. The compound tested typifies compounds used in isolators. It is seen that the largest variations for the two design-level strains (i.e., 50% and 100%) was 11%.

An interesting exercise was to combine cyclical effects and temperature effects. The compound tested was a small variant of the above compound and from a practical viewpoint can be considered identical. Tables 2 and 3 show the ratio of shear modulii between the first and sixth cycle at different temperatures. The ratio increases as the temperature decreases.

TABLE 3. CYCLICAL-TEMPERATURE EFFECTS ON SHEAR MODULUS (100% SHEAR STRAIN)

Temperature		Shear Modulus, G (psi)		
(°C)	(°F)	G_1 (1st Cycle)	G_6 (6th Cycle)	Ratio G_1/G_6
40	104	123	119	1.06
23	73	157	136	1.15
10	50	172	147	1.17
0	32	186	158	1.18
-10	14	219	175	1.25
-20	-4	284	205	1.38

AGING EFFECTS

Seismic isolation bearings must maintain their load carrying capability and seismic response characteristics for the complete life of the structure. For nuclear power plants, a typical design life is 60 years. For civil structures, the design life may be 100 years. Thus, it is important to know the extent that the material properties vary over the design life of the structure. ANL has not performed aging tests for the elastomer compounds reported on here. However, some information is available in the open literature, and this data can be used to get an approximation of the stiffness variation with time. Aging characteristics for a low damping rubber bearing were reported by Nakazawa et al. (1991). Table 4 shows the predicted increase in stiffness due to aging up to 100 years. For the design life of a nuclear power plant (60 years), the bearing stiffness is estimated to increase by 18%. For civil structures with a 100 year design life, the increase in stiffness is estimated to be about 21%. These values could vary from compound to compound, but they can be considered representative.

TABLE 4. ESTIMATED AGING EFFECT ON SHEAR STIFFNESS

Years	Increase in Shear Stiffness (%)
5	3
10	7
30	13
60	18
100	21

TABLE 5. SYSTEM FREQUENCY VARIATIONS

Factor	Maximum Stiffness Change (%)	System Frequency Change (%)
Dimensional	7	3
Frequency	15	7
Temperature	53	24
Cyclical	11	3
Aging	21	10
Combined Temperature-Aging	85	36

SYSTEM FREQUENCY VARIATIONS

The above section identified five factors that could affect the stiffness of high damping elastomer isolation bearings. However, the designer is ultimately interested in the effect that the stiffness variations have on the frequency of the isolation system. Equation (1) shows that the frequency varies directly as the square root of the stiffness and inversely as the square root of the mass. Table 5 lists the maximum variations for each of the identified factors and the resulting variation in system frequency. It is seen that variations in stiffness due to dimensional tolerances only changes the frequency by 3%. In contrast, temperature effects could increase the stiffness of the isolation system by about 53%, which would result in a 24% increase in the frequency of the isolation system. Note, this would only apply to regions of the country that would reach the extreme cold temperatures. The effects of elastomer aging could produce a 10% increase in system frequency at the end of the design life. A combination of aging and temperature effects could increase the stiffness by 85% and, thus, increase the frequency by 36%.

Table 6 shows the modified system frequency obtained by applying the effects of the different factors. Two original systems were considered; the first had a system frequency of 0.5 Hz and the second had a system frequency of 0.75 Hz. The table shows that the 0.5 Hz system could have its frequency raised to 0.62 Hz at the cold end of the temperature range. At the end of life and at the cold end of the temperature range the frequency could be raised to 0.80 Hz. For the original 0.75 Hz system, the frequency could be raised to 1.13 Hz at the end of life and the cold end of temperature range.

TABLE 6. MODIFIED SYSTEM FREQUENCY

Factor	Original System Frequency of 0.5 Hz	Original System Frequency of 0.75 Hz
Dimensional	0.51	0.77
Frequency	0.54	0.80
Temperature	0.62	0.93
Cyclical	0.52	0.77
Aging	0.55	0.83
Combined Temperature Aging	0.80	1.13

CONCLUSIONS

The results of recent research at Argonne National Laboratory has examined the effects that several factors have on the stiffness of high damping elastomer isolation bearings and the resulting variation on the isolation system frequency. The factors identified were the following: dimensional tolerances, frequency effects, temperature effects, cyclical effects, and aging effects.

For isolation systems that are located in regions that experience extremes of temperatures, the effect of material property variation with temperature can play a significant role on the response characteristics of the isolated structure. The temperature effects had the largest influence on modifying the system frequency when extreme cold temperature was considered. Cold temperature (-20°C/-4°F) could increase the stiffness of the isolation system by 53% and the frequency by 24%.

The factor that had the second largest influence on the stiffness of high damping elastomer isolation bearings was the effect of aging. Aging effects could increase bearing stiffness by 21% and increase the isolation system frequency by 10% at the structures end-of-life (100 years).

A combination of cold temperature and aging could produce the largest variations. It was shown that a system with a design frequency of 0.5 Hz could have an end-of-life frequency of 0.80 Hz during the period for which the bearings are at -20 C (-4 F). Under similar conditions, a system designed for 0.75 Hz could change to 1.13 Hz.

The results of this research can be used by isolation bearing designers to determine realistic variations in the response of seismic isolation systems that use high-damping laminated elastomer seismic isolation bearings. For geographical locations that do not experience the temperature range used here, the system frequency variation over the life of the structure will not be as large.

ACKNOWLEDGMENTS

Work performed under the auspices of the U. S. Department of Energy, Technology Support Programs, under Contract W-31-109-Eng-38.

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