RECOVERY CHARACTERISTICS OF HIGH DAMPING ELASTOMERS USED IN SEISMIC ISOLATION BEARINGS

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ABSTRACT

The protection of nuclear and civil structures from the destructive effects of earthquakes has been the focus of intense research and development throughout the world. Seismic isolation is an effective means for reducing and even eliminating the devastating consequences of earthquakes on people, equipment and structures. Engineers have developed many devices for implementing the seismic isolation strategy and the most effective and economical ones have been identified through the test of time. One of these devices is the laminated elastomeric isolation bearing. The behavior of high damping elastomer bearings during several recent earthquakes has shown that they are a viable device for mitigating the effects of earthquakes.

In this paper, results are presented from recent tests on two different elastomers. The first is a highly filled, high modulus, high damping elastomer and the second is a highly-filled, low modulus, high damping elastomer. The stiffness recovery characteristics of the high modulus elastomer subjected to beyond design basis strains and the results of seven years of aging on the low modulus elastomer are presented.

INTRODUCTION

The protection of nuclear and civil structures from the devastating effects of earthquakes has been the focus of intense research and development throughout the world. Seismic isolation is an effective means for reducing and even eliminating the devastating effects of earthquakes on people, equipment and structures. For over a decade, Argonne National Laboratory (ANL) has been involved in R&D activities (Seidensticker, 1991) on the implementation of seismic isolation for nuclear power plants (NPPs). NPPs can be classified as low-to-medium rise structures, thus, ANL's research also applies to low-to-medium rise civil structures, such as, bridges, buildings less than ten stories, etc.

The method chosen for isolating advanced nuclear reactor plants is seismic base isolation. The main reason for this choice is that seismic isolation uses passive devices, which have been proven to be effective as shown by Coveney (1991). Base isolation provides protection to the structure and its contents, and, thus, functional operations can continue during the quake or be resumed shortly thereafter. With this design strategy, a seismic isolation device is placed between the ground and the structure. The isolators effectively decouple the structure from the strong earthquake motion. The importance of using a passive device cannot be over stressed. There is no dependance on people, power supplies, electronic controls/devices, or complex mechanical systems.

The 1994 Northridge California quake and the 1995 Kobe Japan quake have demonstrated the effectiveness of the use of elastomeric isolators for earthquake protection. The base-isolated University of Southern California University hospital had no structural damage or content damage and continued operation during and after the Northridge quake. An earthquake that registered 7.2 on the open-ended Richter scale occurred in Kobe Japan. Reports indicated that the seismically isolated West Japan Computer Center of the Ministry of Post and Telecommunications, which is a 6-story concrete building, survived the quake without damage to its structure or contents. The peak ground acceleration at the center was 0.3 g, and the acceleration above the isolators was attenuated to 0.1 g. A five story concrete building, which was about one kilometer from the center, recorded a peak acceleration of 1.0 g at the roof level. The excellent performance of isolated structures during these two earthquakes provides *in-situ* proof of the effectiveness of seismic isolation for mitigating earthquake damage.

Research and development efforts at Argonne have covered a wide spectrum that includes technical specifications, elastomer specimen testing, scale-size bearing tests and *in-situ* bearing tests. Many investigations were done to find the material response

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characteristics of several elastomers by using small pads of the elastomer bonded to flat metal bars or cylindrical discs. The results of these tests have been reported periodically and are given in the following: Kulak and Hughes (1992), Kulak (1992), Hughes and Kulak (1994), Kulak and Hughes (1994a), Kulak and Hughes (1994b), Kulak and Hughes (1995) and Kulak (1996).

The earlier compounds used in elastomer bearings typically had damping values of approximately 10% at a shear strain of 100%. Extensive testing of these compounds has been done and their response characteristics are fairly well understood. However, over the past five years, there has been an effort to increase the energy dissipation (damping) of the elastomer compounds to address issues raised when long period ground motion is considered. The typical design frequency range for isolation systems is from 0.5 Hz to 0.75 Hz, which also happens to be in the frequency range for long period ground motion. Some new compounds have been developed with damping values of 17% at 100% shear strain. The response characteristics of these higher damping compounds need to be evaluated before they can be employed with confidence in seismic isolation bearings.

In 1988, an international collaboration between the Shimizu Corporation of Japan and Argonne was established to test full size laminated elastomer bearings under a test building at Tohoku University in Sendai Japan. The National Science Foundation sponsored the research efforts at ANL. One of the goals of the project was to develop a low modulus, high damping elastomer for use under lighter-weight structures, such as the Tohoku University building. A low modulus, high damping elastomer was developed by Rubber Consultants of the United Kingdom and used in bearings that were installed under Tohoku University building (Wang et al., 1993). Some results for the *in situ* creep behavior of these bearings was reported by Coveney et al.(1993).

This paper addresses the recovery characteristics of one of the new higher damping compounds and the implications on acceptance testing of isolators made from the compound. The paper also reports on the effects that seven years of aging had on one of the elastomer specimens of the compound used in the bearings installed at Tohoku University.

ELASTOMER TESTING

This section describes the elastomer testing facility, the types of tests specimens and the compounds that were used in this work.

Test Facility

A facility for testing small elastomer specimens has been established within the Reactor Division at Argonne. The main test apparatus is a high precision dynamic testing machine manufactured by Instron Corporation. The 8500 series universal testing machine is a servohydraulic machine with a 55 kip load frame, 5 kip actuator and can comfortably perform tests over the range of interest for seismic isolator response, which is from 0.005 Hz to 5 Hz. For the specimens used to date, strain level testing has been performed up to 350% shear strain, which is well beyond current practice design values. A pentium computer has been programmed to control the test, gather the data, and perform postprocessing.

Test Specimen Types

There are several different specimen configurations currently in use. The ASTM recommends a four-bar configuration that has four elastomer pads with dimensions 25.4 × 25.4 × 6.4 mm (1 × 1 × 1/4 in.), as shown in Fig. 1. LTV Corporation of Texas uses a three-bar configuration (Fig. 2) that has two elastomer pads of the same dimensions as the ASTM specimens. A third configuration is used in the United Kingdom. The UK specimen uses two 25.4 mm (1 in.) diameter by 6.4 mm (1/4 in.) thick cylindrical pads bonded between three steel cylinders. ANL has fabricated grips for all three specimen configurations and can, thus, perform high precision dynamic tests on all specimen configurations.

Recently, Murota et al. (1997) performed tests on four-bar and three-bar shear specimens that had elastomer pads made from the same compound. The conclusions drawn from the study on high damping rubber compounds were (1) for cyclical tests, only slight differences in elastomer response were found in the hysteresis loops and (2) for failure tests, the four-bar specimen had a slightly higher value for the breaking stress.

The results reported here were obtained from four-bar specimens (ASTM type) for the recovery study and from the three-steel cylindrical specimen (UK type) for the aging study.

Elastomer Compounds

A variety of elastomer compounds have been used in the manufacture of elastomeric bearings. These compounds have a range of stiffness, damping, and temperature sensitivity. Low stiffness compounds are suited for light structures, while stiffer compounds are best for heavier structures or where displacement must be limited.

Initially, only natural rubber was used in seismic isolators. The need to incorporate damping into the system was achieved by either using external damping devices or incorporating dissipation directly into the isolator. The lead rubber bearing has a center core of lead that provides energy dissipation. High damping rubber bearings are compounded with fillers that provide additional energy dissipation when the bearings are strained.

Over the past decade, ANL has acquired specimens made from seven different compounds. The results presented here are from two of these compounds. The recovery tests were performed on specimens provided by ALGA of Italy, who worked in conjunction with the Malaysian Rubber Producers Research Association (MRPRA) to develop the compound. The compound reported on here is an ultrahigh-damping elastomer with an effective damping of about 17% at 100% shear strain.

The aging test was done on a rubber compound developed by the MRPRA (currently, Tun Abdul Razak Research Centre) and used in bearings manufactured by Rubber Consultants of Hertford England, which were installed under the Tohoku University building.

Response Characterization

The mechanical response of elastomers can be characterized by two quantities: shear modulus and energy dissipation/damping. The shear modulus of the elastomer determines the fundamental horizontal frequency of the isolation system, and the energy dissipation primarily controls the amplitude at the fundamental frequency. Several definitions have been used for the shear modulus. Here an effective shear modulus, G_{eff}, is used; it is given by

$$G_{eff} = \frac{\Delta\tau}{\Delta\gamma} = \frac{\tau_{max} - \tau_{min}}{\gamma_{max} - \gamma_{min}} \tag{1}$$

where τ_{max} and τ_{min} are the maximum positive and negative shear stresses, respectively, and γ_{max} and γ_{min} are the maximum positive and negative shear strains, respectively.

The second important quantity for predicting the performance of elastomeric isolation systems is energy dissipation during a cycle. Energy dissipated per cycle is calculated by numerically integrating 100 data points from the hysteresis loop.

Another measure of energy dissipation/damping is the equivalent loss angle, δ, which is given by

$$\sin\delta = \frac{4\,W_d}{\pi\;\Delta\tau\;\Delta\gamma} \tag{2}$$

where W_d is the energy dissipated per cycle, which is the area of the hysteresis loop.

TEST DESCRIPTIONS AND DISCUSSION

The concerns in this paper were to evaluate the recovery characteristics of two different elastomer compounds. The first tests evaluated the response of one of the newer ultra-high damping compounds to overstrain, that is strain beyond the design basis. The second test examined the change in shear stiffness and damping of a specimen that experienced seven years of aging.

Recovery Tests

Initial mechanical characterization tests on specimens provided by ALGA of Italy were reported by Kulak and Hughes (1995). The elastomer was compounded to provide 17% damping at a shear strain of 100%. This is significantly higher than the 10% value of previous high-damping compounds. Tests were devised to study the recovery response of this compound to strains beyond the design level of 100%. Two tests were performed on separate samples. The first specimen was over strained to 150% and then retested at the design strain of 100%. The second specimen was over strained to 300% and then retested at 100%.

The tests were conducted in the following manner. The specimens were carefully attached to the test machine with the minimum of prior deformation. Baseline response values for both specimens were obtained at 100% shear strain at a frequency of 0.5 Hz. Next, the specimen was subjected to the overstrain and allowed to rest for four months. The specimen was then retested at 100% shear strain for 20 fully reversed cycles. A second 20-cycle test was performed after a 3 hr. recovery period, and a third 20-cycle test performed 15 min. later.

The recovery response for the first specimen, which was over strained to 150%, is shown in Fig. 4, and it is seen that the first specimen (150% maximum strain) recovered to within 98% of its initial loading stiffness after the 4-month recovery period. The recovered value after the 3 hr. rest period was about 91% of the preceding tested value. The tests performed 15 min. later gave near identical results.

The second specimen was over strained to 300% and did not recover as well as the specimen that was strained to 150%. Figure 5 shows that the specimen only recovered to about 82% of its initial value, which may indicate that the specimen may have sustained permanent internal damage.

Previous work on the softening and recovery of small strain modulus for filled elastomers has been reported by Fletcher and Gent (1953), Medalia (1978), and Coveney and Ahmadi (1989). These authors found that recovery of small strain modulus in the first few minutes after large strain deformation (conditioning) was very rapid; thereafter, recovery continued but beyond about 20 minutes was orders of magnitude slower. Furthermore, the larger the strain amplitude, the longer the small strain modulus took to recover.

Aging Test

Six UK type elastomer specimens were made as part of the international collaboration project with Shimizu corporation. In 1990, these specimens were initially tested by Rubber Consultants to find the variations of shear modulus and loss angle with shear strain. At the end of 1997, one of these specimens was retested (Coveney et al., 1998) and the results are shown in Figs. 6 and 7. Figure 6 shows that the shear modulus increased, on average, by 15% during the seven year period. Table 1 below shows the increase with strain level.

Table 1. Effect of Aging on the Shear Stiffness. Initial Test Performed in 1990 and Second Test Performed in 1997. (Data for Sixth Cycle at 0.5 Hz)

Strain (%)	G_{90} (MPa)	G_{97} (MPa)	G_{97}/G_{90}
10	0.69	0.77	1.12
20	0.58	0.67	1.15
30	0.53	0.62	1.17
50	0.46	0.53	1.15

This increase in stiffness would raise the system frequency by 7%; thus, since the original design frequency was 0.5 Hz, the affect of aging would be to increase it to 0.54 Hz, which is insignificant. The loss angle of the specimen was also tested at the beginning of the project and at the seven year interval. The results are shown in Fig. 7 and tabulated in Table 2 below.

Table 2. Effect of Aging on the Loss Angle. Initial Test Performed in 1990 and Second Test Performed in 1997.

Strain	δ_{90} (degrees)	δ_{97} (degrees)	δ_{97}/δ_{90}
0.1	11.6	12.4	1.07
0.2	10.0	10.5	1.05
0.3	9.2	9.5	1.03
0.5	8.3	9.1	1.10

Some information on aging is available in the open literature, and this data can be used to gage our results Aging characteristics for a low damping rubber bearing were reported by Nakazawa et al. (1991). Table 3 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%. Note, these values are for a low damping compound and, thus, other compounds with high damping characteristics could have different values. Furthermore, part of the change recorded in our tests may have been due to small changes in test procedure. So an apparent increase in stiffness of 15% over a seven year period, approximately double the estimate for the low damping compound, is not an unexpected result.

Table 3. Estimated Aging Effect on Shear Stiffness

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

The specimens used in the above test contained two small coupons (25.4 mm diameter and 6 mm thickness) of the elastomer and probably do not truly represent the degree of aging that would occur in the bearing. Recently, Ahmadi et al. (1993) conducted aging tests on 150 × 150× 30 mm blocks of a high damping natural rubber at elevated aging temperatures. One of their conclusions was that the oxidative aging, which takes place within about 5-8 mm from the surface, increases the stiffness much more than the anaerobic aging that takes place in the bulk. Thus, oxidative aging may have occurred over 40-60% of the specimen. On the other hand, the aging tests reported by Ahmadi were conducted at elevated temperatures: 7 days at 100° C and 14 days at 70° C. The specimen tested here was kept at the laboratory ambient temperature, which was about 22° C. In view of this, these results would represent an upper bound on the aging related increase in stiffness.

CONCLUSIONS

A series of tests has been performed on two different elastomers that were compounded by different companies. The tests were performed to find the recovery characteristics of a new high modulus, ultrahigh damping compound and to evaluate the effect of 7 years of aging on an older low modulus, high damping compound.

Results from the recovery tests show that when the elastomer is strained beyond the design strain (100%) by 50%, the elastomer recovers to within 90% of its design stiffness within 3 hours and requires 4 months to recover 98% of the initial stiffness. In contrast, when the elastomer is over strained by 200%, it only recovers 85% of its design stiffness after 4 months. These results indicate that bearings that are moderately over strained during an earthquake will be less stiff during aftershocks earthquakes that would occur within 4 months. In addition, bearings that are highly over strained during acceptance testing should not be used in isolation systems. An additional observation from these tests is that the elastomer compounds do recover, especially at or below the design strains and, thus, scragging of a bearing before installation is not important. An elastomeric isolator that was installed about 4 months before an earthquake occurred would probably behave more like a virgin elastomer than a scragged elastomer.

The results from aging tests on a low modulus, high damping elastomer showed that during a 7 year period the test specimen had an increase in stiffness of about 15%, which would increase the system frequency by about 7%. However, because the specimens were small, oxidative aging would occur over a higher percentage of the elastomer volume than would occur in the actual bearings. Thus, the stiffness increase observed in the test would be an upper bound for the bearings.

The research reported here provides data that is useful to seismic isolation system designer and should help them to evaluate elastomers. Also, this research shows that as new compounds are developed they must be thoroughly tested to fully characterize their mechanical performance.

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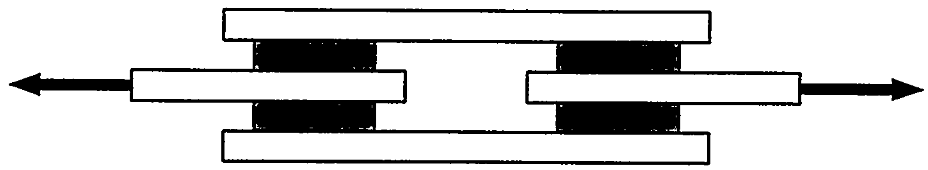

Figure 1. Configuration for an ASTM four-bar specimen.

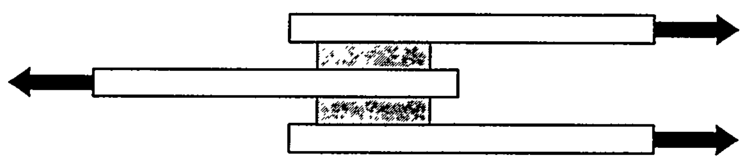

Figure 2. Configuration for LTV three-bar specimen.

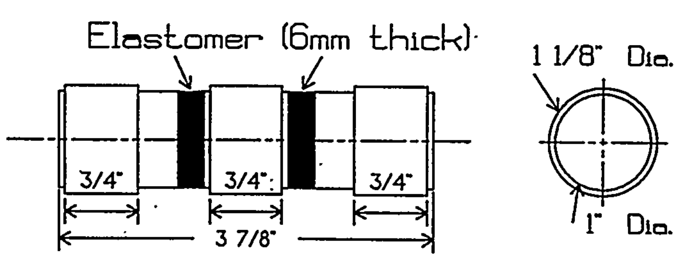

Figure 3. Configuration for UK specimen.

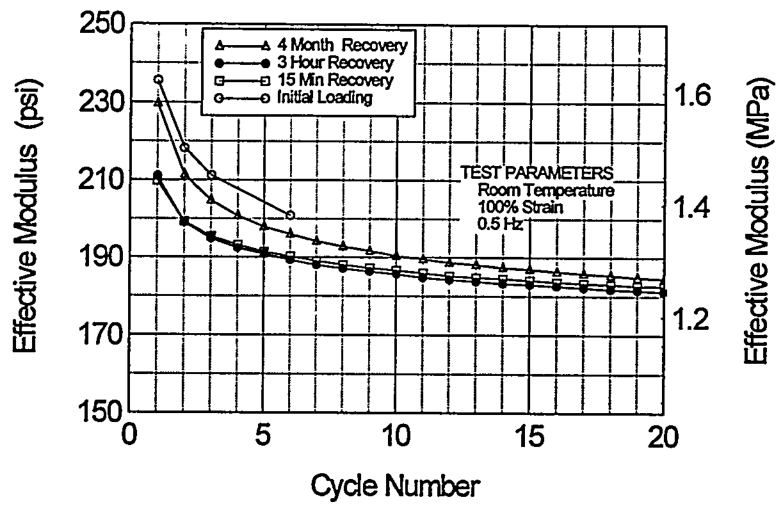

Figure 4. Variation of shear modulus with recovery interval for the case of 150% maximum strain after initial loading.

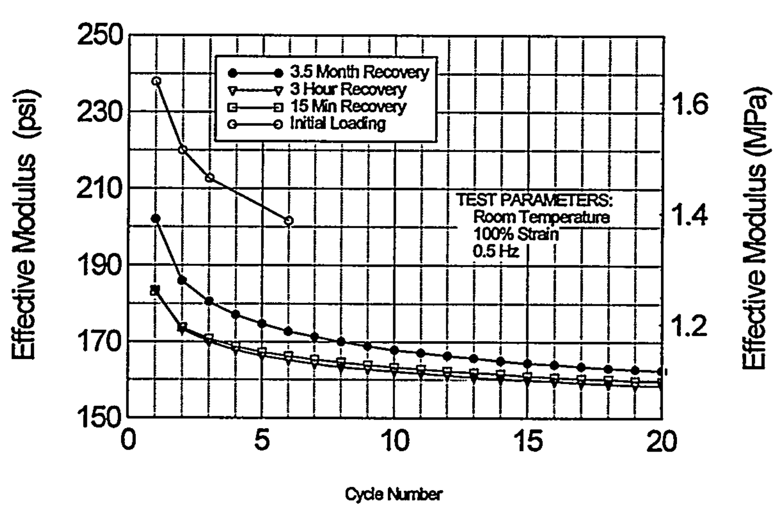

Figure 5. Variation of shear modulus with recovery interval for the case of 300% maximum strain after initial loading.

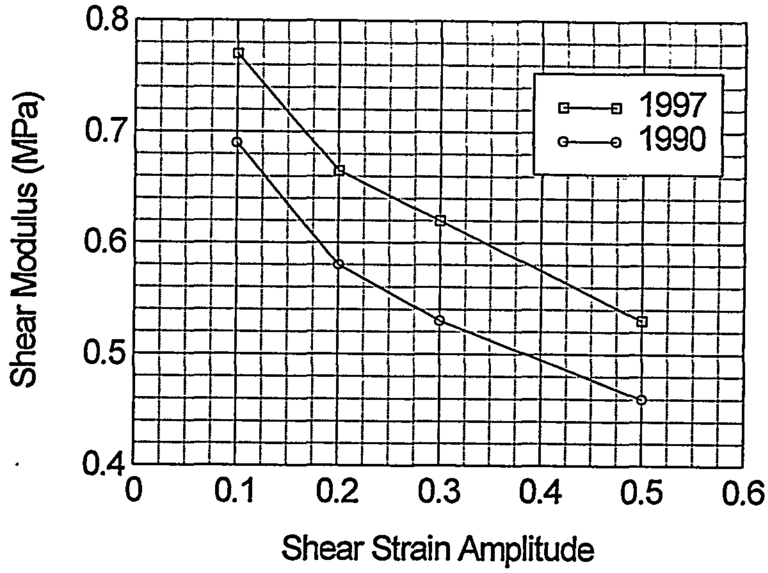

Figure 6. Aging effects on shear modulus. Initial tests performed in 1990 and second test performed in 1997.

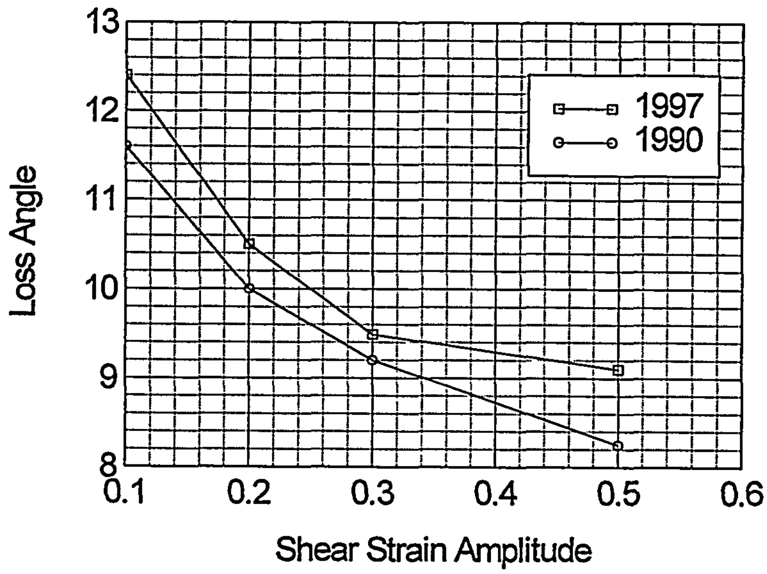

Figure 7. Aging effects on equivalent loss angle. Initial tests performed in 1990 and second test performed in 1997.