TECHNICAL SPECIFICATIONS FOR THE SUCCESSFUL FABRICATION OF LAMINATED SEISMIC ISOLATION BEARINGS

by

R. F. Kulak
Argonne National Laboratory
Argonne, Illinois U.S.A.

ABSTRACT

High damping steel-laminated elastomeric seismic isolation bearings are becoming a preferred device for isolating large buildings and structures. In the United States, the current reference design for the Advanced Liquid Metal Reactor uses laminated bearings for seismic isolation. These bearings are constructed from alternating layers of rubber and steel plates. They are typically designed for shear strains between 50 to 100 percent and expected to sustain two to three times these levels for beyond design basis loading considerations. The technical specifications used to procure these bearings are an important factor in assuring that the bearings meet the performance requirements of the design. The key aspects of the current version of the Technical Specifications are discussed in this paper.

INTRODUCTION

The use of seismic base isolation has been increasing rapidly for such critical facilities as computer centers, medical centers, and emergency control facilities. Base isolation has been employed in many buildings in the United Kingdom and Europe to control unwanted vibrations from subway systems. In New Zealand, road and rail bridges have been the most common structures isolated. Italy used seismic isolation on several bridges, civil buildings and industrial structures. They are devoting considerable effort to this technique. Base isolation has also been used in Greece, the former USSR, and China. The Western United States has several buildings that employ seismic isolators. Japan has been the most aggressive in adapting isolation to their structures. Now, they have more than fifty buildings that use or plan to use seismic isolation. Seismic isolation is beginning to be accepted for use in nuclear facilities as evidenced by its employment in two French designed nuclear power plants: Cruas-Meysee, France and Koeberg, South Africa.

The laminated elastomer bearing is emerging as a preferred device for large buildings/

structures (i.e., with no more than eight stories in height). Bearings that were used in the United Kingdom have experienced more than 30 years of service and have performed well. Laminated bearings have been used for both new construction and retrofitting existing structures. For example, the Salt Lake City and County Building, which was completed in 1894, was retrofitted with laminated elastomer bearings. The United States and Japan are seriously considering this design strategy for some of their future plants. The Advanced Liquid Metal Reactor (ALMR), which currently is the reference design in the United States, uses laminated bearings.

Currently, there are two designs for the laminated elastomer bearing. One design relies on a central lead plug (cylinder) to provide damping, and the other uses a special rubber compound to dissipate energy. As part of the U.S. program to evaluate the performance of these bearings, Argonne initiated an experimental test program. The program, however, only considered the highly damped rubber type of bearing because of time constraints. More than fifty bearings were purchased and tested. Several different designs were tested to evaluate the effects of shape factor, shear modulus, damping and mounting connection. The bearings were purchased from several manufacturers. The U.S. Department of Energy (DOE) and the National Science Foundation (NSF) funded the program.

Early in this research effort, it became clear that the technical specifications used to procure the bearings were critical in obtaining high quality bearings that would perform as designed during an earthquake. The experience gained has shown that a balance between a prescription based and a performance based specification was optimum. Under specification can lead to an inferior bearing and over specification can lead to a bearing that cannot be made or one that is unnecessarily expensive.

Recent experience has shown that the specifications must consider the manufacturing process and the type of bearing testing equipment available at the plant. For example, the design frequency of a typical isolated structure is between 0.4 and 0.8 Hz. Bearing manufacturers, however, do not have test machines that can operate in this frequency range. Typically, manufacturers perform stiffness tests at a frequency of 0.005 Hz. The value of the bearing stiffness called for in the technical specifications must be adjusted to compensate for the much lower testing speed. Also, the paper presents other significant findings.

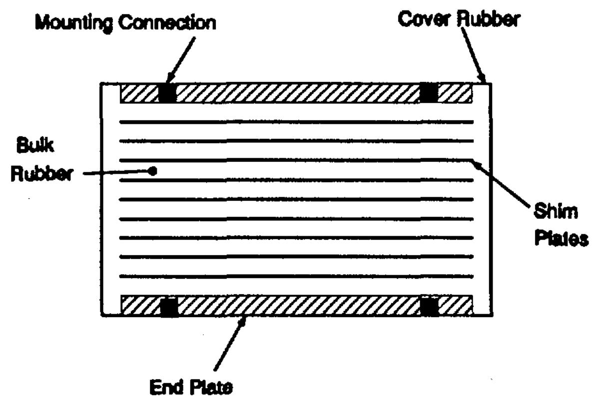

Fig. 1. Typical Steel-Laminated Elastomer Seismic Isolation Bearing.

LAMINATED ELASTOMER BEARINGS

The laminated bearing (Fig. 1) is constructed from alternating thin layers of elastomer and metallic plates (shims) that are bonded together during the vulcanization process. The elastomer is usually a carbon filled natural rubber that exhibits damping when subjected to shear. Recently, some blends of natural and synthetic rubbers have appeared. A thick plate is at each end of the bearing for mounting to flange plates that, in turn, are attached to the basemat and upper structure. In the United States, two methods have been used to attach the bearing to its flange plates: bolts and dowels. Recent tests results show bolting is the better of the two. A cover layer (jacket) of rubber encases the bearing to provide protection from environmental factors. In some designs, this cover layer is a special blend of rubber, and in others it is the same rubber as the bulk rubber of the bearing.

CODES AND STANDARDS

A set of codes and standards for structural steel, rubber and quality control and inspection are given in the American Society for Testing and Materials Standard[1] (ASTM), The British Standard[2] (BS) and the Military Specification and Standards [3] (MIL). Generally, these standards (Table 1) are followed in the steel-laminated elastomeric seismic isolation bearing specifications. As seen from the table, these codes and standards pertain to structural steel, rubber, quality control and inspection. In areas where more specific guidance is required, explicit requirements and procedures are given in the Technical Specification document itself. Some of these specific areas are discussed in this paper. Note, a standard specifically for steel-laminated seismic isolation bearings does not exists. ASTM D 4014 only provides guidance for steel-laminated elastomeric bridge bearings. These bearings do not see the strain levels experienced by seismic isolation bearings during an earthquake.

BEARING DESIGN PARAMETERS AND MECHANICAL PROPERTIES

Perhaps the most important aspect of the Technical Specifications is the specification of the bearing design values. In effect, these are the performance goals the manufactured bearings must meet. Values for the following quantities must be given: dead load, design load, design frequency, design shear strain, ultimate shear strain, stiffness and damping. The elastomer is not required to meet a specific hardness, but hardness measurements must be taken and the value reported.

Stiffness and damping are two important quantities that determine the response of an isolated structure. Because several different definitions for these quantities are being used by designers and isolation bearing manufactures, it is necessary to be very explicit in defining these parameters in the Technical Specifications.

Shear Stiffness

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.

Table 1. Reference codes and standards used for laminated seismic isolation bearings.

Structural Steel	
ASTM A36	Specification for Structural Steel
ASTM A570	Specification for Hot-rolled Carbon Steel Sheet and Strip, Structural Quality
Rubber Strength and Elasticity	
ASTM D395	Test Methods for Rubber Property - Compression
ASTM D412	Test Methods for Rubber Properties in Tension
ASTM D429	Test Methods for Rubber Property - Adhesion to Rigid Substrates
ASTM D518	Test Method for Rubber Deterioration - Surface Cracking
ASTM D573	Test Method for Rubber Deterioration in an Air Oven
ASTM D1149	Test for Rubber Deterioration - Surface Ozone Cracking in a Chamber (Flat Specimens)
ASTM D1229	Test Method for Rubber Property - Compression Set at Low Temperatures
ASTM D1415	Standard Test Method for Rubber Property - International Hardness
ASTM D2137	Test Methods for Rubber Property - Brittleness Point and Flexible Polymers and Cooked Fabrics
ASTM D2240	Test Method for Rubber Property - Durometer Hardness
ASTM D4014	Specification for Plain and Steel-Laminated Elastomeric Bearings for Bridges with Annex (A1-Determination of Shear Modulus)
BS 903	Methods of Testing Vulcanized Rubber: Part A15 - Determination of Creep and Stress Relaxation
Quality Control and Inspection	
MIL-I-45208A	Inspection System Requirements

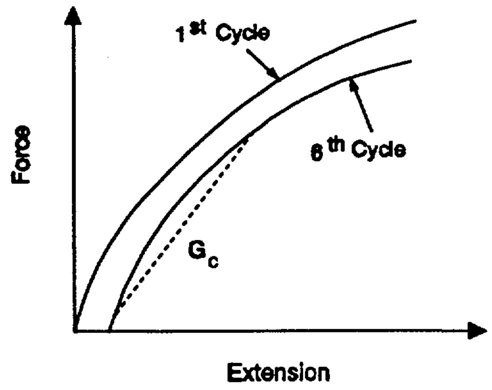

Fig. 2. Cord Shear Modulus as Defined in ASTM D 4014.

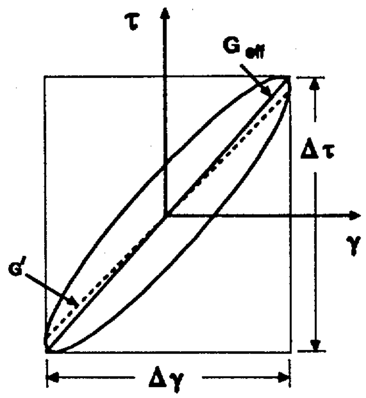

Fig. 3. Definitions of Shear Moduli.

However, there are several different definitions being used for this quantity. ASTM D4014, which was established for steel-laminated elastomeric bridge bearings, defines a cord shear modulus at approximately the 50 percent strain level (Fig. 2). Since current practice uses design shear strains up to 100 percent, a strict adherence to this standard would not provide any useful information. Also, a "cord" modulus is not much use to a designer of seismic isolation systems. Rubber compounders use storage, loss or complex moduli, and seismic isolation system designers uses an effective modulus. The difference in these moduli is shown below. The storage modulus, G', is given by

$$G' = \frac{\tau(\gamma^{+}_{max}) - \tau(\gamma^{-}_{max})}{\gamma^{+}_{max} - \gamma^{-}_{max}} \tag{1}$$

where γ^{+}_{max} and γ^{-}_{max} are the maximum positive and negative shear strains, respectively, that occur during a complete hysteresis loop, and $\tau(\gamma^{+}_{max})$ is defined to be the shear stress at γ^{+}_{max}. The effective shear modulus, G_{eff}, is given by

$$G_{eff} = \frac{\Delta\tau}{\Delta\gamma} = \frac{\tau^{+}_{max} - \tau^{-}_{max}}{\gamma^{+}_{max} - \gamma^{-}_{max}} \tag{2}$$

where τ^{+}_{max} and τ^{-}_{max} are the maximum positive and negative shear stresses, respectively. Figure 3 shows the shear moduli. Note, for typical low strain (e.g., 50 percent) hysteresis loops Eqs. 1 and 2 can give values that differ by 12 percent. Since the values needed for Eq. 2 can be determined with greater accuracy, this definition has been chosen to define the bearing stiffness. Note, values for the storage, loss and complex moduli are not specified in the document, however, these quantities must be measured and their values reported.

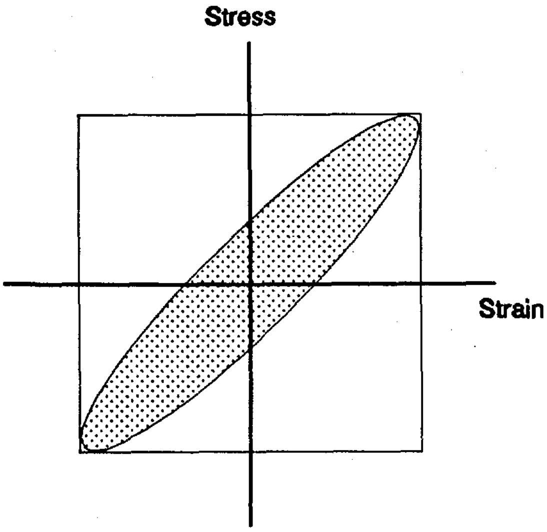

Fig. 4. Energy Dissipated During a Cycle Shown as Shaded Area.

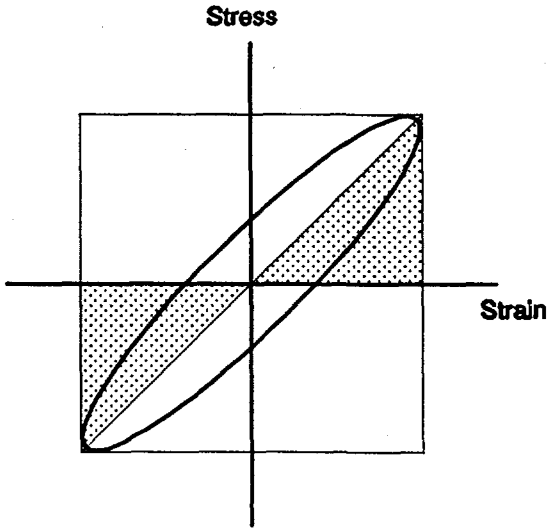

Fig. 5. Stored Energy During a Cycle Shown as Shaded Area.

The definition chosen for the shear modulus must be explicitly spelled out in the technical specifications. Otherwise, the compounder may choose a shear modulus definition other than the one intended by the designer and produce an elastomer with a shear stiffness outside the design range.

Damping

Damping is another quantity used to characterize elastomers. Like stiffness there are several terms used to describe damping: loss angle, loss tangent, damping ratio, percent of critical damping and effective damping ratio. In our specifications the effective damping ratio was chosen as the measure of damping. The effective damping ratio, η is defined by

$$\eta = \frac{U_D}{2\pi U_S} \tag{3}$$

Here U_S is the energy stored during a cycle and U_D is the energy dissipated during the cycle. Figures 4 and 5 illustrate these quantities.

ELASTOMER SPECIMEN TESTING

The material property specification for the elastomer and the testing for those properties

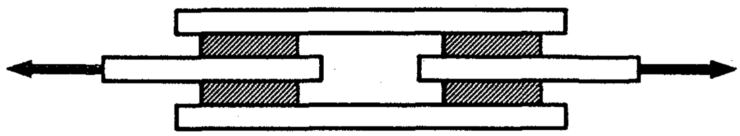

Fig. 6. ASTM D4014 Style Four-Bar Shear Specimen.

is an important part of the process for producing a successful bearing. Values for the following properties are given in the specifications: (1) minimum elongation at failure, (2) minimum tensile strength, (3) effective shear modulus at the design shear strain and design frequency, (4) minimum damping ratio at the design strain and design frequency, and maximum damping ratio at the design strain and design frequency.

The determination of the shear response of the elastomer requires the use of a special test specimen. A test procedure and a suggested test specimen for shear tests are included in ASTM D 4014. This procedure only considers non-reversed cyclical loading, that is from zero to the target strain. The suggested specimen has two sets of rubber pads attached to four steel bars (Fig. 6). To obtain shear data used for earthquake type loading, fully reversed cyclical shear testing must be performed. Experience has shown that the four-bar specimen becomes unstable during fully reversed cyclical testing. Engineers at LTV Energy Products Co. (Arlington TX) developed a three bar lap shear specimen (Fig. 7) that retains stability during reversed cyclical loading. There are two rubber pads in the specimen each being, nominally, 1 x 1 x 0.2 inches. ANL currently uses this design for all its elastomer testing and requires this type of specimen in the Technical Specifications.

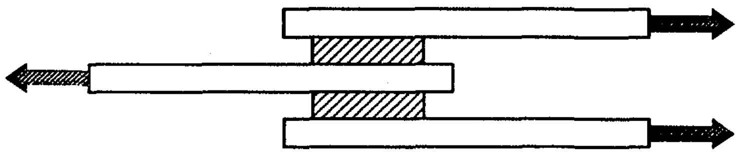

Fig. 7. LTV Style Three-Bar Shear Specimen.

Recent experience has shown that the specifications must consider the manufacturing process and the type of bearing testing equipment available at the plant. For example, the design frequency of a typical isolated structure is between 0.4 and 0.8 Hz. Note, bearing manufacturers do not have test machines that can operate in this frequency range. Typically, manufacturers perform stiffness tests at a frequency of approximately 0.005 Hz, which is two decades lower than current design frequencies. Figure 8 shows the variation in shear modulus with frequency at a shear strain level of 100 percent. The results were obtained from tests performed at Argonne using LTV style three bar lap shear specimens. The value of the bearing stiffness called for in the technical specifications must be adjusted to compensate for the much lower testing speed. In the United States, a bearing testing machine with the capacity to test medium sized bearings at the design frequency is available at the Earthquake Engineering Research Center (EERC) at the University of California at Berkeley and a large capacity machine is available at the Energy Technology Engineering Center (ETEC) at Rockwell International Corporation.

A requirement of the specifications is to submit plots for all stress-strain tests to the buyer. These plots are used to verify that the elastomer meets the specified values at the design strain and design frequency. They also provide additional data on the variation of the mechanical properties over the testing range.

Assuring that the bond strength between the rubber and steel is adequate, is one important goal of the specifications. The standard adhesion strength tests (ASTM D429 Method A) and peel strength tests (ASTM D429 Method B) are required. In addition, the specifications require that shim plates be removed from the production line and used in the bond tests. The specifications require the removal of the "worst" looking shim plate from the production batch for use in a peel strength test. By following this procedure a check on the production process is obtained.

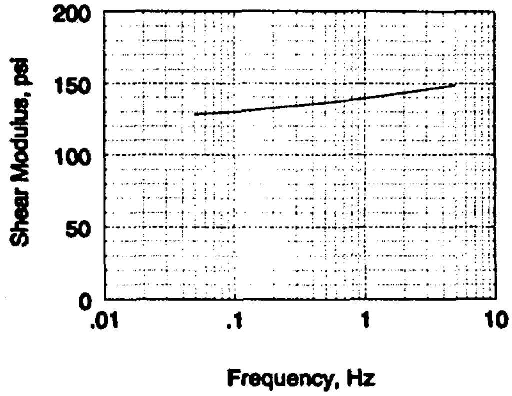

Fig. 8. Variation of Shear Modulus With Frequency at a Strain Level of 100 Percent.

FABRICATION

The bearings are molded as a unit and vulcanized under heat and pressure. The manufacturer must provide complete and detailed process control procedures and specifications for buyer approval before fabrication.

The manufacturer must mold a special proof-of-process bearing to verify the vulcanization process. The test bearing is molded without the use of bonding agents. After vulcanization, the steel and rubber layers are separated, and the rubber layers inspected to evaluate the cure throughout the bearing. Hardness readings (Durometer/IRHD) must be taken across the top and middle elastomer layers. A diametric line (Fig. 9) is divided into eleven (11) intervals and readings taken at the center of the intervals. The readings should be reported. The hardness readings can be related to the shear modulus, and the manufacturer can then judge if the vulcanization process produced the desired shear modulus throughout the bearing. All layers should be visibly examined for defects (e.g., porosity). Each layer should be measured to check the layer thickness for uniformity. Production bearings (i.e., with bonding agents) will be made only after a satisfactory vulcanization process has been verified.

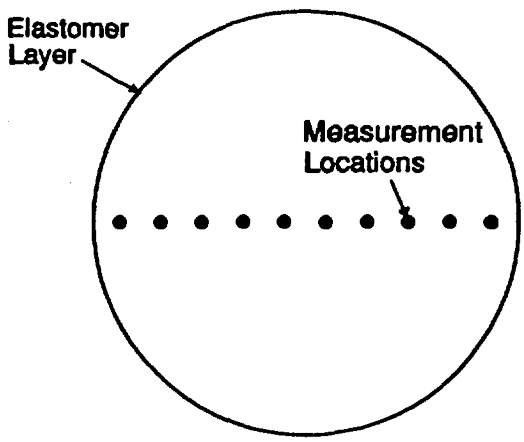

Fig. 9. Location of Hardness Measurements on Laminates of Proof-of-Process Bearing.

COMPLETED BEARING TESTS

A series of tests are performed on the completed bearing. These include a sustained compression test, compression tests and combined compression and shear tests. The sustained compression test subjects the bearing to 1.5 times its design load for 24 hours. Visual inspections for failures, such as debonding of rubber-to-steel and surface cracks, are required during and after the tests. Note, for bearings with thick cover layers, it may not be possible to detect debonding from this test.

The most valuable tests performed on the completed bearing is the combined compression and shear tests series. The first test in this sequence is a compression shear test performed with the bearing loaded to its compressive design load and subjected to five complete reversal loading cycles to plus and minus the design shear strain. The test is performed at 200 sec/cycle (0.005 HZ). This test determines the shear stiffness of the bearing. However, as stated earlier, the value of this stiffness must be adjusted to account for the slower testing rate.

In earlier versions of these specifications, the above shear-compression test was the only test required. Because of Argonne's experimental testing program of elastomeric seismic isolation bearings, it was learned that the above test may not detect poor bonding. The large compressive loading generates enough friction to preclude poor bearing performance and prevent detection of faulty bonding. This can be viewed as a positive safety feature for seismic isolation systems that are designed to have all bearings in compression during an earthquake. However, the manufactured bearings should be properly bonded and the following test was added to the specifications to assess bond integrity. Immediately following the successful completion of the above test, the combined compression-shear test is repeated with the vertical load reduced to zero. The manufacturer must visually inspect the bearing during and after the test, and compare the load-deflection plots for discrepancies between the test with the design axial load and the test with zero axial load.

The bearing manufacturer must submit to the buyer certified reports of the results of all proof testing and other data to show that they have meet the performance specifications prior to bearing shipment. The bearing must be protected from damage during shipment to the final destination.

CONCLUSIONS

Technical Specifications for the procurement of steel-laminated elastomeric seismic isolation bearings have evolved from a set of pre-existing codes and standards from the following sources: the American Society of Testing Materials (ASTM), The British Standard (BS) and the Military Specification (MIL). Since these codes and standards were not specifically written for laminated seismic isolation bearings, they had to be supplemented with additional guidelines. These additional guidelines came from discussions with bearing manufactures, bearing designers and bearing research engineers.

Some key findings of the research are summarized below. It was found that cyclical testing of the elastomer and bearing is needed to obtain performance characteristics during earthquake type motions. A special testing fixture, which maintains stability under cyclical reversed loadings, is required for elastomer specimen testing. Definitions for stiffness and damping must be clearly stated to assure that the rubber compounder and bearing designer are using the same terms. The first bearing must be molded without the use of bonding agents so that a post mortem examination of the elastomer layers can be performed to validate the vulcanization process. The test machines that bearing manufacturer's use to proof test completed bearings operate at frequencies that are several orders of magnitude lower those found in the earthquake spectrum. Thus, the testing speed of the proof test must be considered when evaluating the bearing for acceptance. The completed bearing must be tested in shear under zero or, perhaps, some tensile load to detect faulty bonding.

The research that has lead to these technical specifications is still underway. It is expected that some additional guidelines will be added in the future. However, these will be in a fine tuning category. These Technical Specifications bridge the gap between the performance goals of designers and the constraints imposed by the manufacturing process.

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REFERENCES

The following are global references for the specific codes and standards cited in the text.

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2. British Standards Institute, England.

3. Military Specifications and Standards Service, Information Handling Services, 15 Inverness Way East, P. O. Box 1154, Englewood, CO 80150 USA.