Conf-9203135--1

TECHNICAL SPECIFICATIONS FOR THE SUCCESSFUL FABRICATION OF LAMINATED SEISMIC ISOLATION BEARINGS

ANL/CP--75716

DE92 011845

by

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ABSTRACT

High damping laminated elastomeric bearings are becoming one of the preferred devices 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 bearing 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 that are installed under nuclear structures meet the performance requirements of the design. The key aspects of the current version of the Technical Specifications are discussed in this paper.

INTRODUCTION

On a worldwide basis, the use of seismic base isolation has been increasing rapidly for such critical facilities as computer centers, medical centers, and emergency control facilities. The Western United States has several buildings that employ seismic isolators. On a global domain, Japan has been the most aggressive in adapting isolation to their structures. Now, more than fifty buildings use or plan to use seismic isolation. From the various devices proposed for seismic isolators, the laminated elastomer bearing is emerging as one of the preferred device for large buildings/ structures (i.e., no more than eight stories in height). The laminated bearing 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.

Laminated elastomer bearings are beginning to be accepted for nuclear facilities. These bearings have been employed for the seismic isolation of two French designed nuclear power plants: Cruas-Meysee, France and Koeberg, South Africa. 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 United States reference design, uses seismic isolation. As part of the U.S. program to evaluate the performance of these types of bearings, Argonne initiated an experimental test program. Over fifty bearings have been purchased and tested. Several different designs were tested to evaluate the effects of shape factor, shear modulus, damping and mounting connection. The bearings have been purchased from several manufacturers. The program was funded by the U.S. Department of Energy (DOE) and the National Science Foundation (NSF).

Early on in this research effort, it became clear that the technical specifications used to procure the bearings was 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 expensive.

Recent experience has shown that the specifications must take into account 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 rate of 14 to 16 in/min, which approximately translates to a frequency of 0.01 Hz for a 6 in. design displacement. The value of the bearing stiffness called for in the technical specifications must be adjusted to compensate for the much lower testing speed. In addition to the above, other significant findings are presented.

CODES AND STANDARDS

A set of codes and standards have been developed for structural steel, rubber and quality control and inspection. The source of these documents include the American Society for Testing and Materials[1] (ASTM), The British Standard[2] (BS) and the Military Specification[3] (MIL). For the most part these standards are adhered to in the bearing specifications. These standards are listed in Table 1 below. 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 key areas are discussed in this paper.

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, this is the bottom line that the manufactured bearings must meet. Values for the following quantities must be given: dead load, design load, design

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

frequency, design shear strain, ultimate shear strain, stiffness and damping.

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 one of the quantities 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. However, there are several different definitions being used for this quantity. A rubber compounder would think in terms of storage, loss or complex stiffness and a seismic isolation system designer would think in terms of an effective modulus. To show the difference in these definitions, the storage modulus, G', is given by

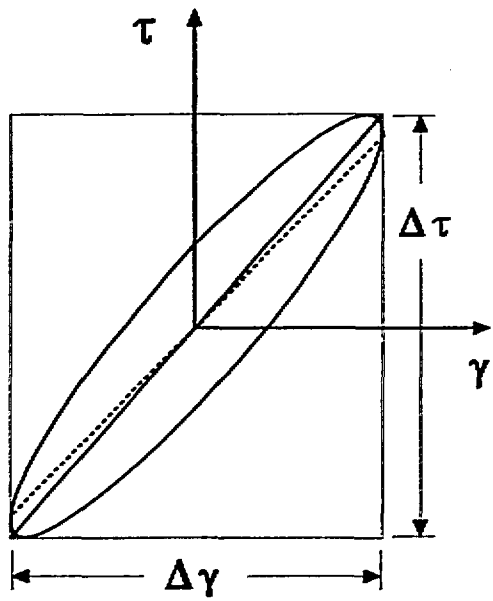

Fig. 1. Definitions of shear modulii. Storage modulus shown as dashed line and effective modulus shown as solid line.

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

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 strain at γ^{+}_{max}. The effective shear modulus, G_{eff}, 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. The shear modulii are shown in Fig. 1. Note, for typical low strain hysteresis loops Eqs. 1 and 2 can give values that differ by about 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.

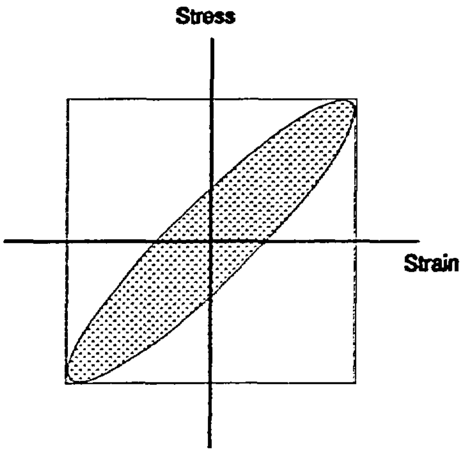

Fig. 2. Energy dissipated during a cycle shown as shaded area.

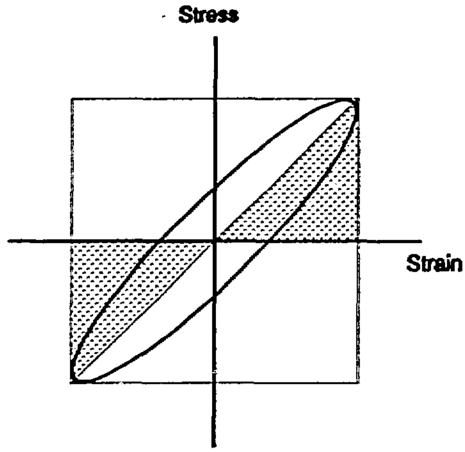

Fig. 3. Stored energy during a cycle shown as shaded area.

It is necessary that the definition chosen for the shear modulus 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 2 and 3 illustrate these quantities.

ELASTOMER SPECIMEN TESTING

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

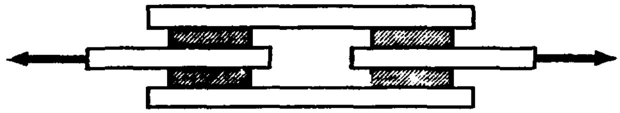

Fig. 4. ASTM D4014 style four bar lap shear specimen.

The determination of the shear response of the elastomer requires the use of a special test specimen. Included in ASTM D4014 is a test procedure and a suggested test specimen configuration for shear tests. This procedure only considers one-sided loading, that is from zero to the target strain. The suggested test specimen configuration consists of two sets of rubber specimens attached to four steel bars as shown in Fig. 4. To obtain shear data relevant to 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. 5) that retains stability during reversed cyclical loading. There are two rubber pads in the specimen each being 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.

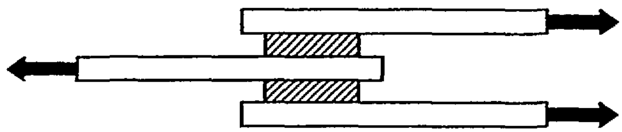

Fig. 5. LTV style three bar lap shear specimen.

Recent experience has shown that the specifications must take into account 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 rate of 14 to 16 in/min, which approximately translates to a frequency of 0.01 Hz for a 6 in. design displacement. The value of the bearing stiffness called for in the technical specifications must be adjusted to compensate for the much lower testing speed. Currently, in the US a bearing testing machine capable of testing 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.

It is a requirement of the specifications that plots for all stress-strain test be submitted to the buyer. These plots can verify that the elastomer meets the specified values at the design strain and design frequency and provides 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 of the important goals 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 specification requires that shim plates be removed from the production line and used in some these bond tests. It is required that the "worst" looking shim plate be removed from the production batch and used in a peel strength test. By following this procedure a check is obtained on the production process.

FABRICATION

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

It is required that a special proof-of-process bearing be manufactured 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. It is required to take Durometer hardness readings taken across the top and middle elastomer layers. A diametral line is divided into ten (10) intervals and readings taken at the center of the intervals. The readings should be reported. The Durometer readings can be related to the shear modulus and the manufacturer can then judge if the vulcanizing process is producing a rubber with 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 uniformity. The production bearings (with bonding agents) shall be made only after a satisfactory vulcanization process has been verified.

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 a period of 24 hours. Visual inspections for failures, such as debonding of rubber-to-steel and surface cracks, are required during and after the tests. It should be noted that for bearings with thick cover layers, it may not be possible to detect debonding from this tests.

Perhaps 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 tests 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. However, as a result 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 would generate 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, it is felt that 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. It is required to visually inspect the bearing during and after the test and to compare the load-deflection plot for discrepancies between the compressive and zero axial load tests.

It is required that the bearing manufacture submit to the buyer certified reports of the results of all proof testing and other data to indicate that he has meet the performance specifications prior to bearing shipment.

CONCLUSIONS

Technical Specifications for the procurement of laminated 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 of the key findings of the research are given below. It was found that cyclical testing of the elastomer and bearing is needed to access its 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 so that the rubber compounder and bearing designer are using the same terms. The first bearing should be molded without the use of bonding agents so that a post mortem examination of the elastomer layers can be performed to evaluate the cure. The test machines that bearing manufacturer's use to proof test completed bearings operate at speeds that are several lower than those that a bearing would experience during an earthquake. Thus, the testing speed of the proof test must be considered when evaluating the bearing performance. The completed bearing must be tested in shear under zero or perhaps some tensile load in order to detect faulty bonding between the metal plates and the elastomer.

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, it is felt that these will be in a fine tuning category. These Technical Specifications are intended to bridge the gap between the performance goals of designers of seismic isolation system that employ laminated isolation bearings and the constraints imposed by the manufacturing process.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the following people with whom he had helpful discussions during the performance of this work: Jack Rainbolt, Gary Whightsil and Mike Hogan of LTV Energy Products Co. in Arlington TX; Vince Coveney of Bristol Polytechnic in England; Keith Fuller of Rubber Consultants in England; Steve Bennett of Furon-Structural Bearing Division in Athens, TX; Jim Kelly of the Earthquake Engineering Research Center at the University of California at Berkeley; Vince DeVita and Paul Chen of Energy Technology Engineering Center in Canoga Park, CA; Fred Tajirian of Bechtel National, Inc. San Francisco, CA; Stan Sitta, Elastomer Consultant in Wheaton, IL; and Ralph Seidensticker, Yao Chang and Tom Hughes of Argonne National Laboratory.

This work was performed as part of the work in the Engineering Mechanics Program of the Reactor Engineering Division of Argonne National Laboratory under the auspices of the U.S. Department of Energy, Contract No. W-31-109-Eng-38.

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.