Study on Seismic Base Isolation of LWR Plants
(Durability Tests of Laminated Rubber Bearings)

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1. Introduction

In general, laminated rubber bearings, while required to possess functions as base isolation devices, are also required to demonstrate functions as supportive structural materials for building superstructures. Accordingly, laminated rubber bearings are required to be durable for numbers of years about the same degrees as the service lives of the superstructures, and further, need to maintain their original functions. In this study, therefore, durability tests using small reduced models were performed to ascertain the durability of laminated natural rubber bearings. In evaluating durability of laminated rubber bearings, it is important to confirm how the functions as laminated rubber bearings (spring constant, breaking characteristics) will change with the environment and use over a long period of time. Therefore, experiments to confirm the items below were conducted for evaluation of the durability of laminated rubber bearings.

1) Influence of temperature of the environment in which laminated rubber bearings are used on the mechanical characteristics of the bearings.
   i)Confirmation tests for temperature-dependent characteristics
2) Influence of aging of rubber resulting from long-term use on mechanical characteristics (including breaking characteristics) of laminated rubber bearings.
   ii)Confirmation tests of time-dependent aging characteristics of laminated rubber bearings
   iii)Excessive displacement loading tests (including breaking tests) of laminated rubber bearings subjected to time-dependent aging

2. Confirmation Tests of Temperature-Dependent Characteristics and Time-Dependent Aging Characteristics of Laminated Rubber Bearings

2.1. Specimens

Small specimens were used because of limitations in the size of the experimentation apparatus. In order to evaluate the durability of laminated rubber bearings of full size by means of small specimens, it is necessary for the stresses and strains applied to the respective rubber bearings to conform to the law of similarity. The specimens used in these experiments were laminated rubber bearings of rated load 10 tons reducing semi-full-size laminated rubber bearings of

SMiRT 11 Transactions Vol. K (August 1991) Tokyo, Japan, © 1991

rated load 100 tons by a given law of similarity. The configuration of a specimen is shown in Fig.1 and the law of similarity between rated load of 100 tons and specimens is given in Table 1. The material of the laminated rubber used for specimens was the same as that used for full-size laminated rubber bearings (natural rubber for laminated rubber and synthetic rubber for the surface rubber).

2.2. Test Conditions

In confirmation tests of temperature-dependent characteristics, since laminated rubber bearings are installed at the foundation of the building and are placed in an environment unexposed to direct sunlight of air temperature -20°C to about 40°C, the outside air temperatures during testing were varied as parameters (the four levels of -20, 0, 20, 40°C). The experiments were conducted by giving horizontal displacements while applying rated vertical load under the above parameter temperatures, thus confirming the influence of outside air temperature on horizontal spring constants. Meanwhile, in confirmation tests of time-dependent aging characteristics, the chemical reaction kinetics theory of Arrhenius that the conversion law of temperature and time holds for an organic material like rubber was followed, and time-dependent aging was accelerated by placing laminated rubber bearings in a constant temperature box under temperatures of given conditions and rated load. The variation in horizontal spring constant due to time-dependent aging was ascertained in accordance with the elapse of time obtained by the conversion law. The time-dependent aging acceleration temperatures chosen for the testing were the three levels; 20°C (average temperature in normal use of laminated rubber bearings), 50°C (consideration given that the estimated number of days accelerated is not too far apart from reality), and 80°C (consideration given that time-dependent aging is not apt to progress because of the form of the laminated rubber bearings). The specimens used in the various tests are given in Table 2 along with their relationships of temperature and test conditions.

2.3. Method of Testing

Loading was only by static force for a set of two laminated rubber bearings. Loading was controlled by displacement, namely positive and negative cyclic loading with horizontal displacement (9.4cm) identical to strain corresponding to allowable displacement (30cm) of laminated rubber bearings of semi-full-sized scale of rated load 100 tons was controlled. The loading method is shown in Fig.2. Loading in confirmation tests of temperature-dependent characteristics was done at the time (after 3days left standing) it was judged that specimens inside the constant temperature box had become uniform. Further, temperature control at the time of loading was done enclosing specimens installed in the loading apparatus in insulating material and using liquid nitrogen at low temperature and a warm-air blower at high temperature. Thermo-couples were used for measuring temperatures, and controlling was done so that temperatures at the specimen surfaces would be the pre-determined temperature ± 3°C. On the other hand, application of load in confirmation tests of time-dependent aging was done at ambient temperature periodically taking out specimens from the constant-temperature box.

2.4 Test Results

(1) Results of Confirmation Tests of Temperature-Dependent Characteristics
The horizontal load-displacement relationships at testing temperature conditions of -20°C and 40°C are shown in Fig.3. The relationships of various testing

temperature conditions with horizontal stiffness are shown in Fig.4, and with equivalent viscous damping constant in Fig.5. In general, the temperature conditions of rubber material is that it has a tendency to harden more the lower temperature. This tendency is seen in the test results, and there are temperature-dependent properties in horizontal stiffness and equivalent viscous damping, and the differences are distinctly apparent in hysteresis configurations also.

(2) Results of Confirmation Tests of Time-dependent Aging Characteristics

The relationships (with 20°C as the basis) of rate of variation in horizontal stiffness at various acceleration temperatures with periods of time-dependent aging estimation are shown in Fig.6. The transitions in time-dependent aging estimation periods and equivalent viscous damping constant are shown in Fig.7. Qualitative variations against transitions in time-dependent estimation periods regarding equivalent viscous damping constant was not recognizable in the test results. However, in the relationships of variation ratios in horizontal stiffness and time-dependent aging estimation period, based on the test results for 1-month passage at acceleration temperature 50°C (estimated number of years approximately 2.3yr.) to 6-month passage at acceleration temperature 80°C (estimated number of years approximately 224yr.), on regression by straight line of the variation ratio of horizontal stiffness, hardening due to time-dependent aging was gradually estimated from around the time approximately 3years had elapsed. Further, in loading tests at the time 12-months had elapsed (estimated number of years approximately 448yr.) at acceleration temperature of 80°C, the surface rubber ruptured (no damage to laminated rubber) so that subsequent the tests were tested as reference.

3. Excessive Displacement Loading Tests (Including Breaking Tests) of Laminated Rubber Bearings Subjected to Time-Dependent Aging

3.1 Specimens

Specimens used were those employed in the confirmation tests of time-dependent aging characteristics for time-dependent aging acceleration temperature 20°C (number of years elapsed 3.5yr.), 50°C (estimated number of years elapsed approximately 100yr.), and 80°C (estimated number of years elapsed approximately 1600yr.: tested as reference).

3.2 Test Conditions

As parameters of the tests, the three levels of rated load 10 tons and 20 tons and 0 ton taking into consideration load variations were set with vertical load as the object. For loading, semi-dynamic positive and negative cyclic loading was done with the parameters set for the respective specimens at the various aging acceleration temperatures, after which one-way monotonic loading was done until breaking. Further, with rated load of 10 tons as the object, one-way monotonic loading was done from the initial state and comparisons were made with the results of one-way monotonic loading after positive and negative cyclic loading. Further, simple tensile loading in the vertical direction assuming the condition of pull-out during rocking of the building was also done. The cycles of positive and negative loading were gradually increased in increments of shear strain 20% with three waves per cycle from shear strain 200% (corresponding to the specimen design allowable displacement : 91mm) to shear strain 400% (excessive displacement range). The one-way monotonic loading and vertical-direction simple tensile loading were done gradually increasing displacement statically until the specimen was breaking. The conditions of the excessive displacement loading tests are given in Table 3, and the concepts of the testing conditions in Fig.8.

3.3 Method of Testing

Loading was done for one specimen at each aging acceleration temperature with loading control by vertical actuator for vertical loading and displacement control by horizontal actuator for horizontal displacement.

3.4 Test Results

With the specimens at the various aging acceleration temperatures as the objects, comparisons were made of the results of one-way monotonic loading up to breaking after positive and negative cyclic loading at rated load of 10 tons and the results of one-way monotonic loading from the initial state up to breaking, and the relationships of horizontal load-displacement are shown in Fig.9. With all of the specimens at the various time-dependent aging acceleration temperatures, compared with breaking displacements when one-way monotonic loading was done from the initial state, the breaking displacements on applying one-way monotonic loading after positive and negative cyclic loading were larger. This increase in breaking displacement was due to alteration in the microscopic characteristics of rubber materials (cross-linked structure, other) caused by cyclic loading, and the differences in loads at the times of breaking could hardly be seen. The breaking characteristics under the various axial forces are shown in Fig.10 according to individual specimens at the various time-dependent aging acceleration temperatures. The relationships of loads and displacements of the results of one-way monotonic loading after positive and negative cyclic loading and vertical-direction simple tensile loading are shown in Fig.11. On comparisons of the results of tests at time-dependent aging acceleration temperature 20°C (number of years elapsed 3.5yr.) and time-dependent aging acceleration temperature 50°C (estimated number of years elapsed, approximately 100yr.), there was hardening with time-dependent aging, and although there were slight decreases in deformation capability and ultimate strength at breaking, extreme reduction in performance was not recognizable.

4. Conclusion

How functions (spring constant, breaking characteristics) as laminated rubber bearings change according to the environment of use and long-term use was ascertained through experiment. The results are summarized below.

- Temperature-dependent was confirmed from the fact that horizontal stiffness and equivalent viscous damping constant became larger as temperature fell from normal temperature.
- Regarding horizontal stiffness, a tendency was seen for hardening to increase with time-dependent aging.
- Deformation capability and ultimate strength at breaking are decreased slightly with time-dependent aging, but it was ascertained that there is no extreme reduction in performance so long as the surface rubber remains sound.

Reference

This report is a summarization of the results of durability tests of laminated natural rubber bearings carried out in "Study on Seismic Base Isolation of LWR Plants" as part of joint research by the electric power industry.

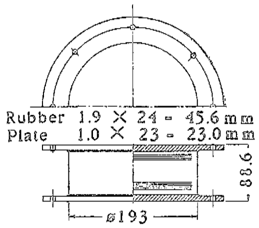


Fig.1 Configuration of Specimen

Table 1
Reduction Ratio

	Reduction Ratio
Length	1/3.16
Weight	$1/3.16^2$
Density	1.0
Stiffness	1/3.16

Table 2 Test Conditions

(a) Temperature-dependency Characteristics

Specimen (No.)	13,14	15,16	17,18	19,20	21,22	23,24	25,26	1,2	3,4
Set Temperature (℃)	-20		0		20			40	

(b) Time-dependent Aging Characteristics

Specimen (No.)	Set Temperature (℃)	Test Conditions								
21,22	20	Test Interval (months)								
23,24		1	3	6	12	18	24	30	36	42
25,26										
1,2	50	Time-dependent Aging Estimation (years)								
3,4		2.3	7	14	28	42	56	70	84	98
5,6										
7,8	80	Time-dependent Aging Estimation (years)								
9,10		38	112	224	448	672	896	1120	1344	1568
11,12										

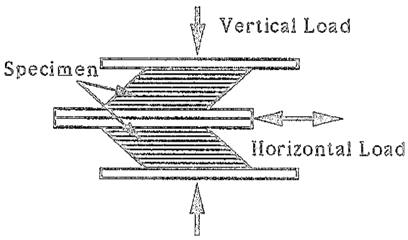
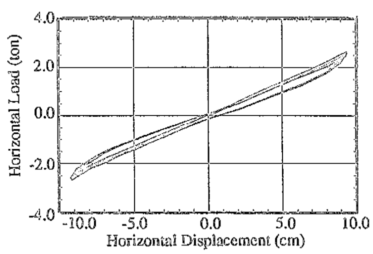
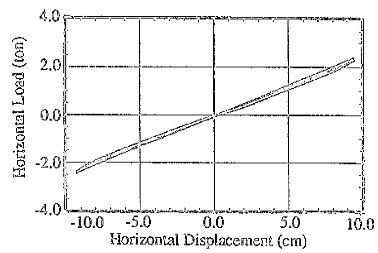


Fig.2 Loading Method



(a) Testing Temperature -20°C



(b) Testing Temperature 40°C

Fig.3 Horizontal Load-displacement Relationships

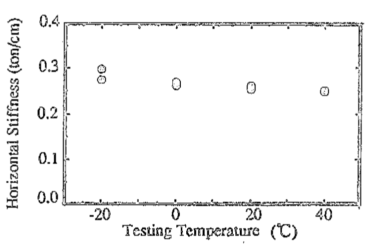


Fig.4 Relationships of Various Testing Temperature Conditions with Horizontal Stiffness

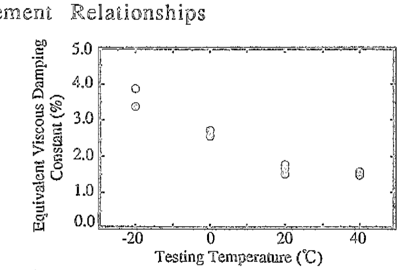


Fig.5 Relationships of Various Testing Temperature Conditions with Equivalent Viscous Damping Constant

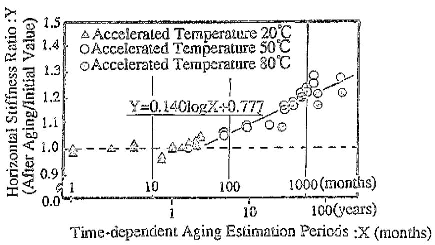


Fig.6 Relationships of Variation in Horizontal Stiffness with Time-dependent Aging Estimation Periods

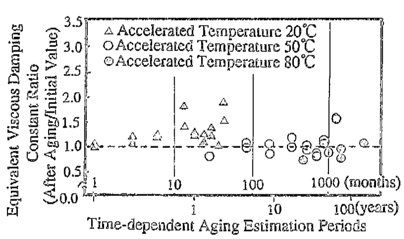


Fig.7 Transitions in Time-dependent Aging Estimation Periods and Equivalent Viscous Damping Constant

Table 3 Conditions of the Excessive Displacement Loading Tests

Specimen No., Condition			Vertical Compression Loading (ton)	Loading Method
20 ℃ Estimated 3.5years	50 ℃ Estimated 100years	80 ℃ Estimated 1600years		
No.21	No.1	No.7	10	Cyclic Loading and One-way Loading
No.22	No.2	No.8	20	Cyclic Loading and One-way Loading
No.23	No.3	No.9	0	Cyclic Loading and One-way Loading
No.24	No.4	No.10	10	One-way Loading
No.26	No.6	No.12	Vertical Tension	One-way Loading

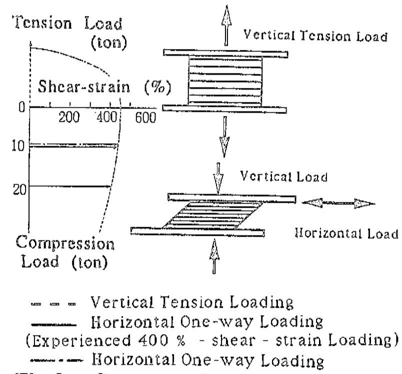
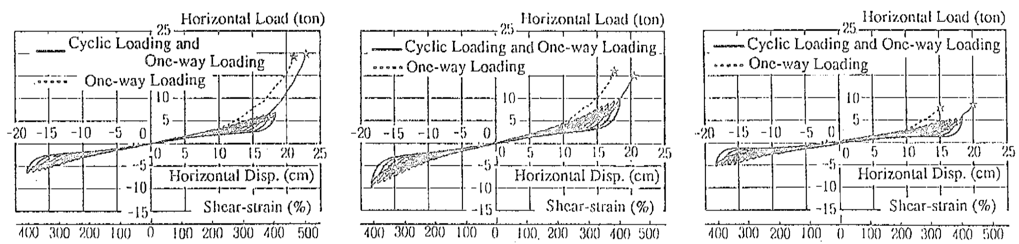
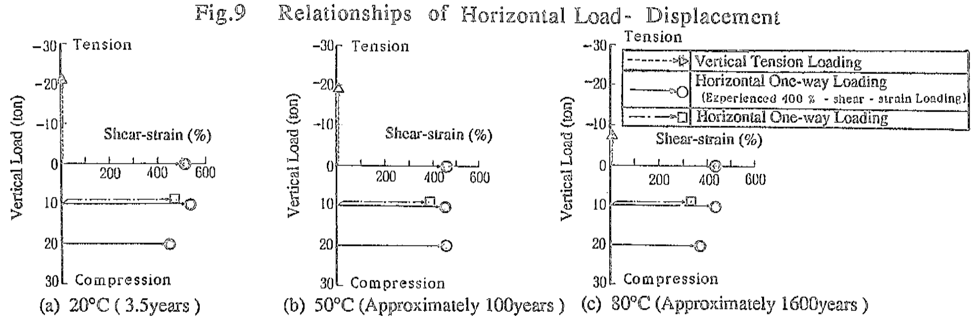


Fig.8 Concept of the Excessive Displacement Loading Tests



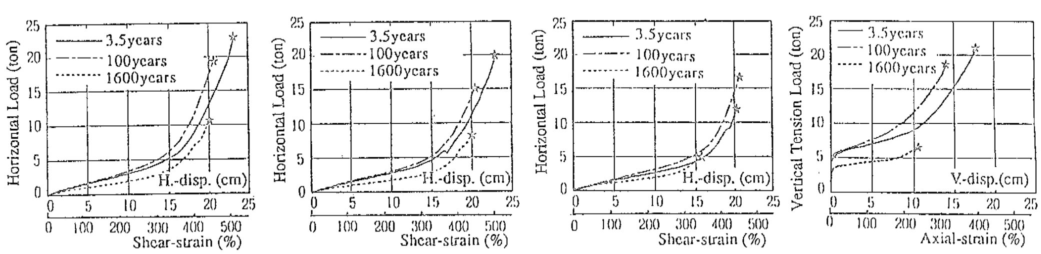
(a) 20°C (3.5years) (b) 50°C (Approximately 100years) (c) 80°C (Approximately 1600years)

Fig.9 Relationships of Horizontal Load- Displacement



(a) 20°C (3.5years) (b) 50°C (Approximately 100years) (c) 80°C (Approximately 1600years)

Fig.10 Breaking Characteristics under the Various Axial Forces



(a) Vertical Compression Load 0ton (b) Vertical Compression Load 10ton (c) Vertical Compression Load 20ton (d) Vertical Simple Tensile Loading

Fig.11 Relationships of Force-Displacement under the Various Axial Forces (One-way Monotonic Loading)